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Source Assessment Sampling System Design and Development

Acurex Corp, Mountain View, Calif Aerotherm Div

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SOURCE ASSESSMENT SAMPLING SYSTEM: DESIGN AND DEVELOPMENT

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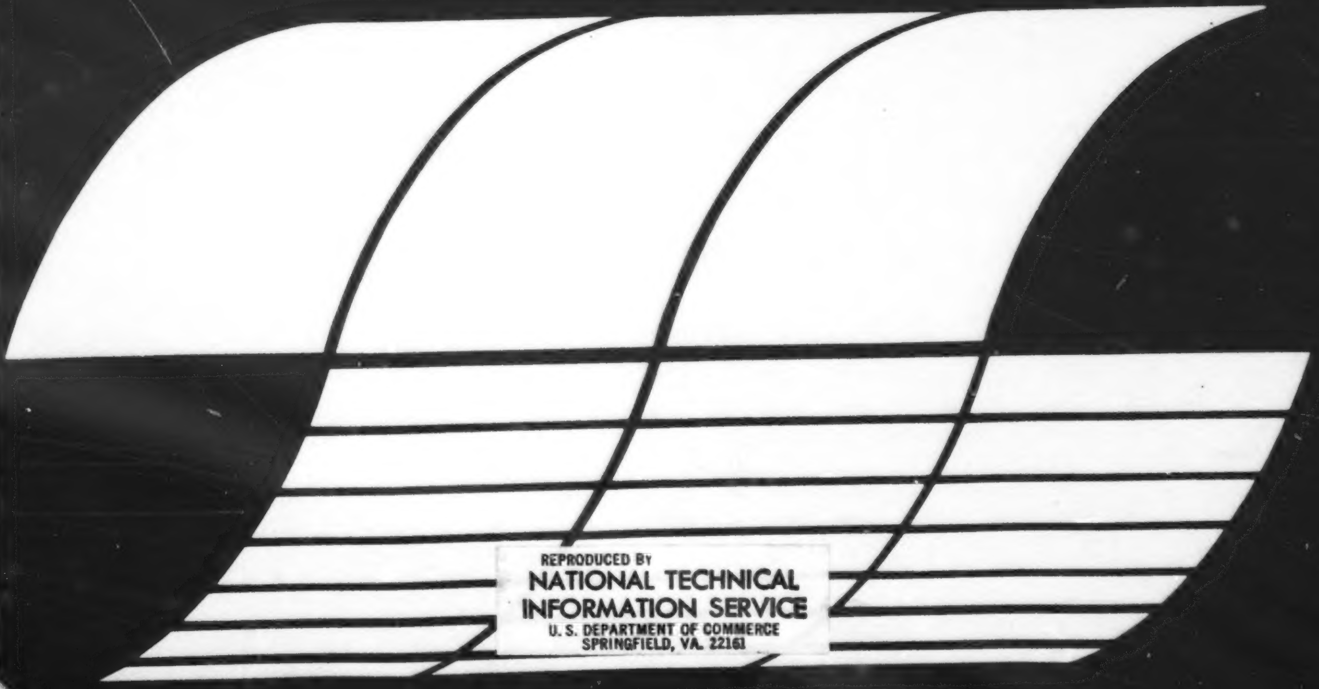

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16. ABSTRACT

The report chronologically describes the design and development of the Source Assessment Sampling System (SASS). The SASS train is the principal sampling element for ducted sources when performing EPA's Level 1 environmental assessment studies. As such, it samples process streams and separates the samples into filterable particulate (four size fractions), organic vapors, and inorganic vapors. The design concept and philosophy are discussed, as well as the evolutionary development of the system. Developmental testing, problem areas, and subsequent system changes are described in detail. The report also includes a complete description of the calibration procedures and system used to determine the size cut points of the particulate fractionating cyclones used.

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Sampling		Stationary Sources	14B	07B
Assessments	Calibrating	Source Assessment Sampling System (SASS)	13H	
Industrial Processes	Cyclone Separators			
Dust		Environmental Assessment	11G	07A
Vapors			07D	
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SOURCE ASSESSMENT SAMPLING SYSTEM: DESIGN AND DEVELOPMENT

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SECTION 1

INTRODUCTION

The Process Measurements Branch, IERL/RTP, has developed a strategy for sampling and analysis in Environmental Assessment Programs (References 1 and 2). Three levels of sampling/analysis detail are specified. Level 1 is a screening approach to measure organic and inorganic mass emissions (within a factor of 2 to 3). Levels 2 and 3 provide quantitative and/or continuous monitoring of specific pollutant species.

The Source Assessment Sampling System (SASS) is the primary sampling tool for Level 1 gaseous and particulate emissions from ducted sources. The SASS train performs the following functions:

- Extractive sampling of gaseous streams from ducts or stacks
- Measurement of particulate mass loading and size distribution
- Collection of organic species for subsequent analysis
- Collection of vaporous trace elements for subsequent analysis

In addition to these functional requirements, the SASS train must be portable, corrosion resistant, easily cleanable, reliable, and accurate. The primary purpose of the project described in this report was to design and construct a sampling train meeting all of these requirements.

During the project, there were several changes in design philosophy. Some changes resulted from improvements of SASS train performance initiated by project personnel, others resulted from changes in Level 1 procedures imposed by EPA. To make clear the progress of this project and the reasons for the various changes, the report has been organized chronologically.

Section 2 describes sampler development efforts that preceded and led to the SASS. Section 3 presents the initial SASS design philosophy and the Conceptual Design Study that was made early in the project. Section 4 reviews the design, construction, and initial testing of a full SASS train based on the recommended conceptual design. Section 5 relates the cyclone calibration history at Southern Research Institute and Acurex. Section 6 discusses the problems reported by field test crews and recommends solutions.

Other documents useful in understanding the design and operation of the SASS include the Operating Manual (Reference 3) and the detail design drawings*. The drawings, part of the contractually-required documentation of the SASS development program, contain all required fabrication information for the components designed.

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*SASS detail design drawings are property of EPA/RTP, Industrial Environmental Research Laboratories. Generated under EPA Contract No. 68-02-2154.

SECTION 2

PRELIMINARY DESIGN HISTORY

To reach its present development, the SASS train has passed through several evolutionary stages. The first stage was the High Volume Stack Sampler (HVSS). This was the first Method 5 sampling tain that operated at high flowrate and was compact, rugged, and easy to set up and use. The immediate precursor of the SASS was the Combustion Power Company train (the CPC train), an adaption of the HVSS to include particulate fractionation by series cyclones.

Although these earlier trains were designed and used for somewhat different purposes than the SASS, they shared with the SASS operation at high volumetric flowrate (that is, they were designed to operate at up to 4 scfm*, compared to about 1 scfm for most sampling trains). In addition, many of the components designed for these early sampling trains have been used with only minor modification in the SASS.

In this section we review the design and method of operation of the HVSS and CPC sampling trains, and discuss how they evolved into the SASS.

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*Throughout this report, numerical quantities are presented in the units most commonly employed by workers in the fields of sampling and analysis. A conversion table is given in Appendix E to allow conversions of nonmetric units to standard S.I. units.

2.1 THE HIGH-VOLUME STACK SAMPLER

The first particulate sampling train developed by EPA personnel was used during the middle 1960's to test municipal incinerator emissions. This train sampled at the rate of 5 cfm. The Control Systems Laboratory (CSL) of EPA used this type of sampling train for evaluating sources between about 1965 to 1972. During this period other EPA personnel needing to sample a large number of sources for establishing emission levels developed a lighter, more compact sampling train with a nominal flowrate of 0.75 cfm.

The original high volume sampling train was bulky, difficult to transport and, in many respects, lacked the refinements of a commercial product. It was clear, however, that for certain applications -- particularly for evaluating the effectiveness of particulate control devices -- there was a need for a high volume sampler for routine field use.

In 1972 Acurex Corporation began developing what came to be known as the High Volume Stack Sampler (HVSS). The HVSS was to conform to the basic requirements of Method 5, Standards of Performance for New Stationary Sources, Federal Register Volume 36, No. 247. The HVSS is made up of a heated probe; an absolute particulate filter housed in a temperature-controlled oven; an impinger and gas drying module for moisture determination; a control module for monitoring temperatures, pressures, and flowrates throughout the system; a vacuum pump; and associated hoses and electrical lines connecting these components. Figure 1 shows the HVSS as designed and constructed.

The specific features of the HVSS are listed below:

- Fiberglass, cushioned cases for carrying and shipping each piece of equipment
- Oil-less vane pump modified for low leakage

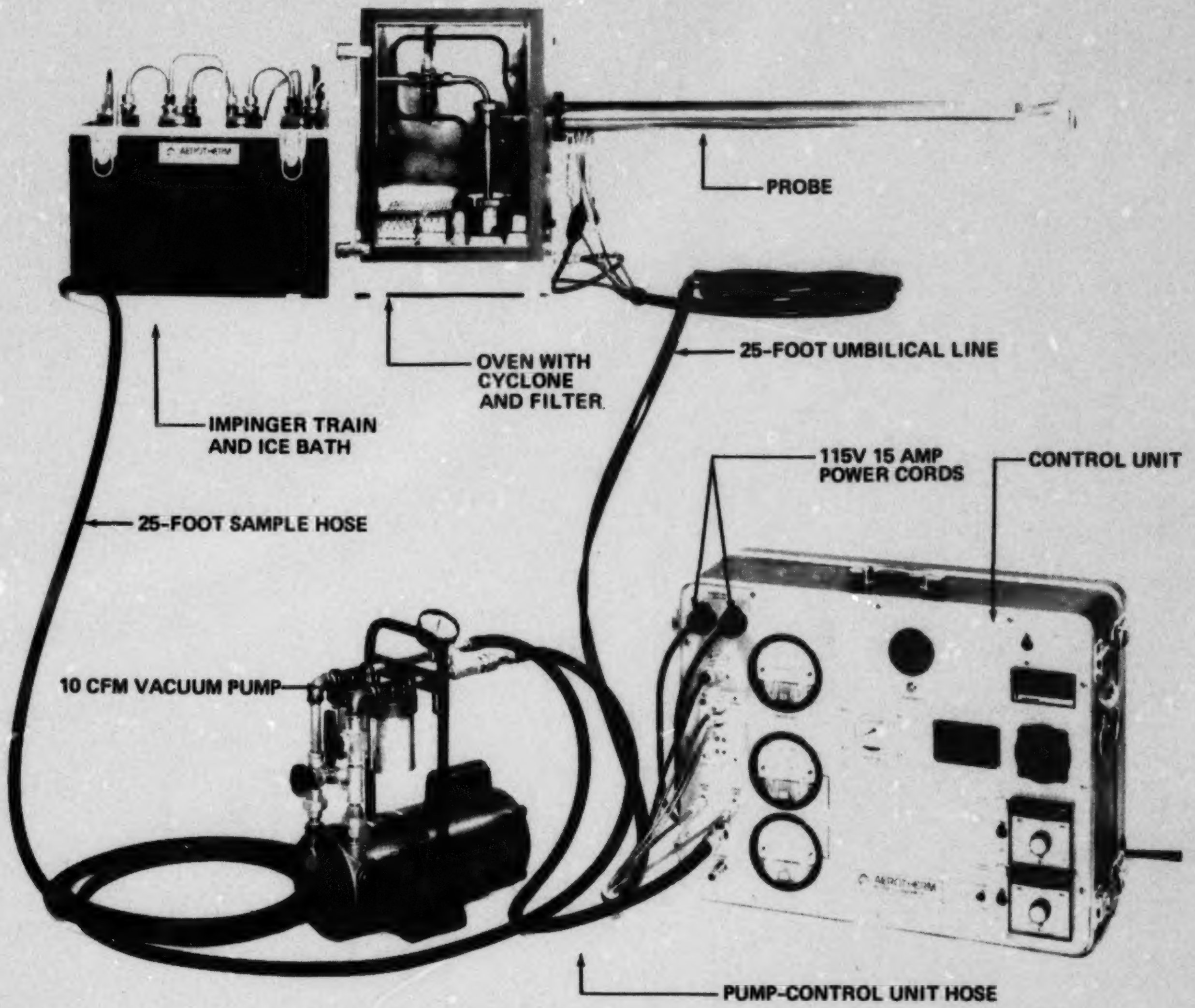
PROBE
25-FOOT UMBILICAL LINE
OVEN WITH CYCLONE AND FILTER
IMPINGER TRAIN AND ICE BATH
115V 15 AMP POWER CORDS
CONTROL UNIT
25-FOOT SAMPLE HOSE
10 CFM VACUUM PUMP
PUMP-CONTROL UNIT HOSE

Figure 1. Acurex high-volume stack sampler.

- Two Magnehelic gages for accurate readout of the pitot tube range of 0 to 4 inches of water
- Round probe body for ease in sealing the sampling port
- Probe can be rotated for sampling horizontal ducts located at same level or below the sampling train
- Impinger train and ice bath separable from oven
- Stainless steel, Lexan, or Teflon used instead of glass -- all glassware eliminated to avoid breakage problems
- Enlarged impinger bottles with demisters to prevent water carry-over at flowrates up to 8 cfm
- Stable unirail traversing stand for guiding probe in horizontal or vertical directions
- Circuit breakers instead of fuses
- Separate power lines for heaters and pump to assure availability of required power

The control module, probe, and vacuum pump from the HVSS have been used without modification on the SASS. The impinger assembly, particulate collection system, and oven were extensively modified. Specific information about SASS component design is given in Section 3. More information about the HVSS can be found in Reference 4.

2.2 THE COMBUSTION POWER COMPANY SAMPLER

The next steps in the development of the SASS were taken in November 1975, when Acurex began designing a special sampling train for tests of the fluidized bed combustor at the Combustion Power Company in Menlo Park, California. This train (which became known as the CPC train) was in essence the "front half" of a SASS. It consisted of a probe, a three-stage cyclone assembly and backup filter, an oven to maintain the cyclones above

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condensation temperatures, an impinger assembly, a vacuum pump and a control module. The train was designed for operation at 4.0 acfm. Development of the CPC train was funded by EPA.

Because the CPC train had to be produced on a tight schedule and limited budget, all of the components were standard HVSS parts except the cyclone assembly and oven. So that four discrete particulate size fractions would be obtained, three series cyclones, with nominal D_{50} cut sizes of 1, 3, and 10 μm, and a backup filter were desired.

Considerable previous work on cyclone design for sampling had been conducted by Southern Research Institute, and their work had led to a design for just such a cyclone train. The train had been built and some limited testing conducted by TRW, Inc. in early 1975 (Reference 5). The cyclones had been designed and constructed according to the standard Lapple design methods (Reference 6). The 1-μm and 3-μm cyclones appeared to be satisfactory for incorporation into the CPC train, with only minor modifications. However, the 10-μm cut-size cyclone, 7 inches in diameter and 30 inches high, was much too large to use in a portable sampling train. In addition, laboratory experiments showed an excessive buildup of dust in the very long inlet to the 10-μm cyclone. Clearly, another cyclone design was required.

Acurex designed, constructed, and tested a "stub" cyclone of 10-μm cut size, but much smaller dimensions, based on the work of Andrew McFarlane at the University of Texas (Reference 7). The cyclone was 7 inches in diameter and 10 inches high, including a large dust collection cup. It achieved the 10 μm cut size in such a small package by controlling the cyclone shape and incorporating vanes to reduce the internal vortices.

This much smaller cyclone allowed the design of a portable three-stage series cyclone assembly and backup filter in an oven of manageable size and weight. The cyclones and filter were closely packed together, and connecting tubing was designed so that the cyclones and filter could be fitted into an oven only about 50 percent larger than the standard HVSS oven. These cyclones, filter, and oven became the basis for the CPC train design, and ultimately, the SASS particulate handling system.

SECTION 3

DESIGN PHILOSOPHY

The basic SASS design philosophy was established by EPA prior to the initiation of our program on March 3, 1976. Figure 2 shows the design schematic for the complete SASS train. This basic design concept has been adhered to throughout the course of the SASS development program.

3.1 CONTRACT REQUIREMENTS

Acurex was awarded a contract to design, fabricate, and deliver three sampling systems for use in environmental assessment studies of industrial and energy processes. These systems were to be designed to meet the following requirements:

1. Extract a sample from a process stream at 3 to 5 cfm
2. Separate the particulate fraction of the sample into four size ranges
   a. >10 micrometers
   b. 3 to 10 micrometers
   c. 1 to 3 micrometers
   d. <1 micrometer
3. The organic fraction shall be adsorbed on a Tenax porous polymer adsorber. Requirements for the adsorber are as follows:
   a. Operating temperature -- not to exceed 60°C

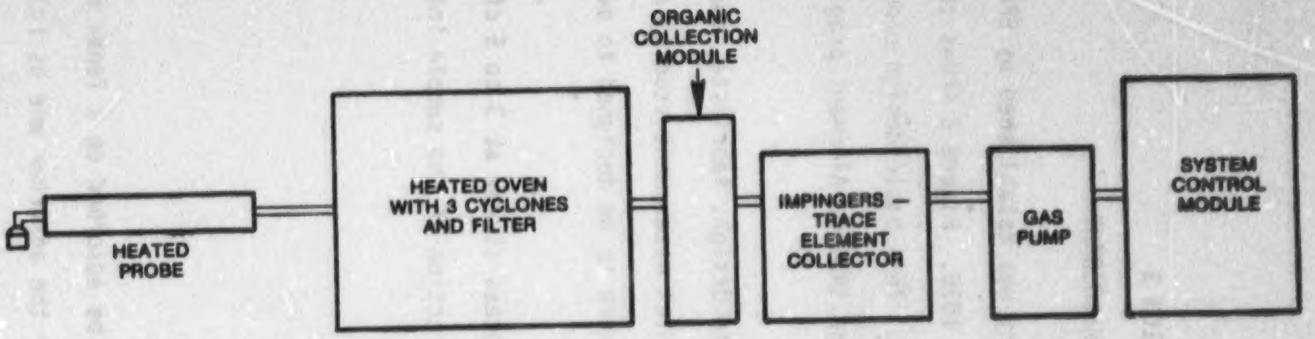

HEATED PROBE
HEATED OVEN WITH 3 CYCLONES AND FILTER
ORGANIC COLLECTION MODULE
IMPINGERS — TRACE ELEMENT COLLECTOR
GAS PUMP
SYSTEM CONTROL MODULE

Figure 2. Design schematic — SASS train.

b. Bed depth -- 70 mm minimum

c. Face velocity -- not to exceed 1.65 ft sec

4. The inorganic fraction shall be collected in scrubbing impingers

3.2 EPA GUIDELINES

At the beginning of the development program EPA suggested guidelines for the detailed design phase. These in included:

1. The cost of the completed SASS train was to be kept as low as possible. A target figure of $17,000 for a barebones, but complete, SASS train was suggested. An additional cost of not more than $3000 was allowable for an automatic control feature in the event that such a feature was judged desirable.
2. The SASS design was to be made as interchangeable as possible with the High Volume Stack Sampler (HVSS). This was felt to be desirable because many of the potential users of the SASS train already owned an HVSS. In some cases it might be possible to upgrade an HVSS to a SASS, cutting costs considerably to users.
3. Cyclones, rather than a stage impactor, were specified as the method for determining particulate size distribution. The primary reasons for choosing cyclones was the desire to collect large particulate samples (~1 gram) for subsequent chemical and biological analysis, and the requirement for trouble-free field use. It was considered necessary to maintain a constant sampling flowrate through the cyclone assembly, since cyclone size cut varies with gas flowrate. However, if the cyclone flowrate is held constant, then isokinetic flow generally cannot be maintained at

the nozzle for the train configuration shown in Figure 2, unless special measures are taken. (Several ways of simultaneously obtaining constant cyclone flow and isokinetic nozzle flow are discussed in Appendix B.)

4. The probe and oven were to be heated to eliminate the possibility of SO_3 or organics condensing.
5. The organic sorbent material in the organic module was to be kept dry and held at 60°C.
6. A flowrate of 4.0 acfm was to be maintained at the cyclones.
7. The only acceptable materials of construction for the SASS parts that would contact the sample stream were to be Type 316 Stainless steel, fully-fluorinated Teflon, or Pyrex glass.
8. The SASS was to be designed for ease of sample recovery and post-test cleanup.

There were several problems with these guidelines. Item 1 (low cost) conflicts directly with Items 2 (SASS to be interchangeable with HVSS) and 8 (limiting the permissible materials of construction). To balance these and other conflicting requirements, a Conceptual Design Study was conducted in which four possible SASS designs were compared for technical feasibility and cost. This design study is discussed in Section 3.4.

Two of the guidelines were changed later in the SASS development program. The sorbent material tempertature (Item 5) was lowered and the sorbent was allowed to contact the condensate. Also, the flowrate at the cyclones (Item 6) was later changed from 4.0 acfm to 4.0 scfm. The reasons for these and several other system changes are discussed in Section 5.

3.3 COMPONENT DESIGN PHILOSOPHIES

The initial design philosophy for each SASS system component was established at a meeting at Acurex on March 10, 1976. Representatives of Acurex, EPA, and TRW, Inc. (the inorganic analysis contractor for the task level of effort program) attended. The meeting was to establish the SASS basic design parameters and to specify the requirements for two "incinerator ship" sampling trains.

3.3.1 Incinerator Train Design and Construction

The incinerator ship trains were to be partial SASS trains for TRW, Inc. to use in assessing the combustion efficiency of the incinerator ship Vulcanus. Because of the inflexible sailing date of the ship, it was considered essential that the trains be delivered to TRW no later than June 1, 1976.

Since the ship was to be burning a liquid chlorocarbon, it was anticipated that particulate would be almost nonexistant, and that organics would constitute the primary pollutant of interest. Accordingly, the organic module would have to be designed, constructed, and tested, but the cyclone assembly would not be required. The remaining components -- impinger assembly, control module, vacuum pump, umbilical, hoses -- would duplicate standard HVSS components to the greatest extent possible. TRW was to supply a special water-cooled probe to withstand the anticipated high incineration temperatures.

The primary task was the design and construction of the organic module. Several conceptual designs were considered, and a thin-film heat exchanger concept was chosen for development. The sample gas was to be cooled to 55°C, condensate removed, then the gas was to be reheated to 60°C and passed through a porous polymer sorbent bed. The detailed design of an organic module was essentially completed on March 25. At that time, EPA directed that the operating temperature of the sorbent be changed to 20°C and any condensate formed allowed to pass through the sorbent. These changes were required due to information on organics retention developed by Arthur D. Little, Inc.

Based on these new requirements, a modified organic module was designed, and two complete incinerator ship trains were constructed and assembled at Acurex in April and May 1976. The incinerator ship trains were delivered to TRW on June 1, 1976, as originally scheduled. The actual sampling of the incinerator ship Vulcanus took place on March 5 to 13, 1977. The materials being burned -- waste and byproducts from the manufacture of alkylchlorides, dichloroethane, vinyl chloride, and epichlorohydrin -- could be classified as primary low molecular weight chlorinated aliphatics. Sampling was successfully accomplished (Reference 8), although the high hydrochloric acid content of the sampled gases caused severe corrosion of some SASS components. Corrosion was observed when temperatures were reduced to a point where condensation of water vapor occurred. The resulting hydrochloric acid produced etching and pitting of the Type 316 stainless steel in the organic module and in the impinger assembly.

Because of the very demanding schedule required to design, construct, test, and ship the incinerator trains in 2 1/2 months, the initial component designs had to be carried through to fabrication. There was simply no time for design changes or exploration of parallel design concepts. In general, this approach produced adequate component designs that became part of the present SASS train. However, in a few cases (discussed in Section 6), some later modifications were made.

3.3.2 Individual Component Design

The individual component design philosophies, established at the March 1976 meeting, are described below.

Probe

A standard Acurex heated probe was selected for the SASS train. This probe was designed for the HVSS system, and had demonstrated good performance at high (2 to 8 acfm) volumetric flowrates. It was decided to use a 316 stainless steel liner rather than glass or quartz, primarily on the grounds of simpler construction and greatly increased durability and reliability.

Oven

Because of the size of the cyclones and filter, the oven is the largest single SASS train component. It is essential, therefore, to minimize its size and weight. The oven previously designed for the CPC train was as small as practicable, given the fixed cyclone size. For the SASS train, the weight was reduced by making the outer shell of the oven out of aluminum. The inner shell was made of stainless steel for corrosion resistance.

Cyclones and Filter

The cyclone assembly designed for the CPC trains was basically satisfactory, although some modifications were required. The CPC cyclones were fitted together with screwed flanges; it was deemed desirable to replace these with quick disconnect aircraft clamps so the cyclone assembly could be rapidly disassembled and cleaned in the field. Also, the CPC cyclones were interconnected in a very convoluted way, making assembly and disassembly difficult. Because some sharp bends in the interconnecting tubing were points of possible erosion or dust buildup, it was felt to be desirable to reconfigure the interconnecting tubing to eliminate these problems.

The filter holder used in both the HVSS and CPC trains had performed satisfactorily in previous field tests. It was used in the SASS with only minimal changes: the materials of construction were changed from 304 to 316 stainless steel, a Teflon O-ring was used rather than Viton, and the Teflon coating was eliminated. The Teflon coating was considered unacceptable because so-called Teflon coatings usually contain impurities to improve adhesion and film-forming.

Organic Module

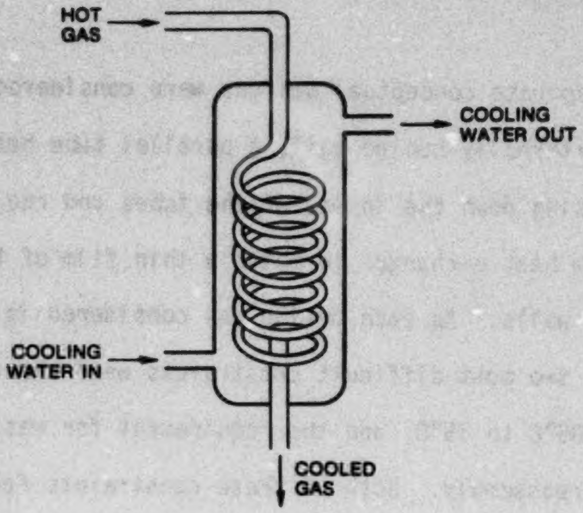
The organic module -- the part of the SASS train for capturing the organic pollutant species -- was a completely new component with no prior design or field history. Accordingly, there was considerable discussion of its form and function. The organics were to be captured by cooling the hot gas stream from the oven and passing the gas through a dry porous polymer bed of Tenax gas-chromatographic resin (although other sorbent materials were under consideration). The organic module was to:

- Cool the gas from the oven (at 205°C to 55°C)
- Collect any condensate formed
- Reheat the gas back to 60°C and pass it through the sorbent bed
- Maintain the sorbent bed at 60°C ± 2°C
- Be easy to disassemble, clean, and reassemble
- Have a low gas pressure drop
- Be constructed entirely of 316 stainless steel, Teflon, or Pyrex

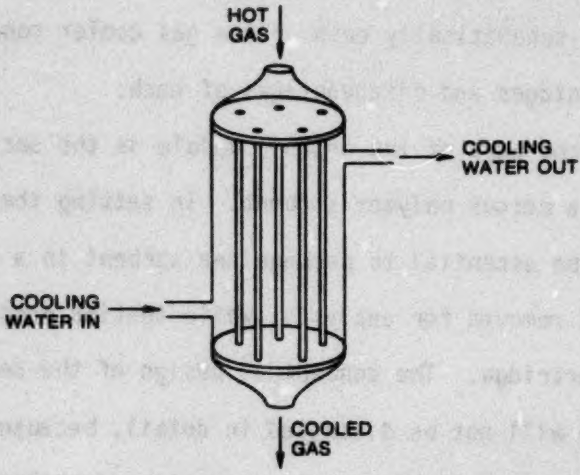
These requirements dictated a two part design: the first part would cool the gas and collect any condensate; the second part would reheat the gas slightly and then pass it through the sorbent bed. Designing the first part -- the gas cooling and condensate collection system -- appeared to be more difficult.

Three separate conceptual designs were considered for the cooling section: an externally-cooled coil, a parallel tube heat exchanger (with the sample gas passing down the inside of the tubes and cooling fluid outside), and a thin film heat exchanger in which a thin film of the sample gas passes between cooled walls. As each design was considered in detail, it became clear that the two most difficult constraints were the requirement to cool the gas from 205°C to 55°C, and the requirement for easy disassembly, cleaning, and reassembly. Both of these constraints favored a design with a large surface area composed of smooth, easily-accessed surfaces. The thin film heat exchanger concept was judged clearly superior in these areas. Figure 3 shows schematically each of the gas cooler concepts; Table 1 lists the advantages and disadvantages of each.

The second part of the organic module is the section where organics are sorbed on a porous polymer sorbent. In setting the design philosophy, it was agreed to be essential to package the sorbent in a replaceable cartridge which could be removed for analysis, while testing proceeded with a clean replacement cartridge. The conceptual design of the second part of the organic module will not be discussed in detail, because about 6 weeks after the start of the project, the operating parameters for the organic module were changed by EPA. The key changes were a reduction in sorbent operating temperature from 60°C to 20°C, and a requirement that condensate pass through the sorbent bed along with the gas. (These changes are discussed in more detail in Section 6.) The effect on the organic

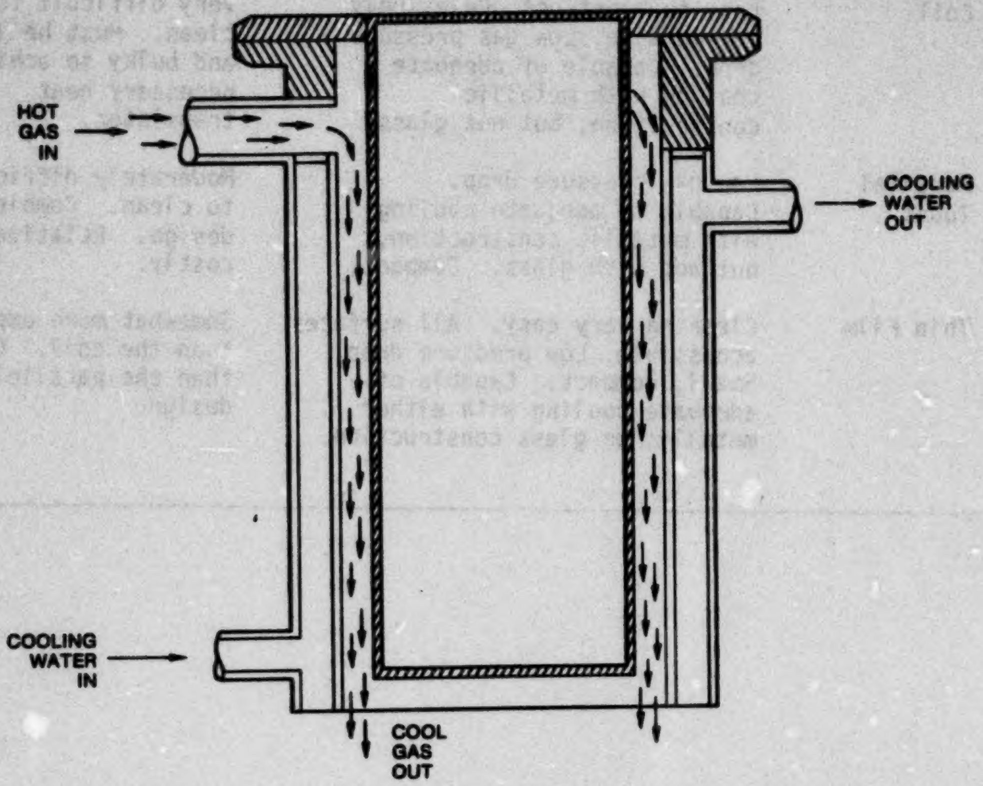

HOT GAS
COOLING WATER OUT
COOLING WATER IN
COOLED GAS

a. Coiled – tube cooler


HOT GAS
COOLING WATER OUT
COOLING WATER IN
COOLED GAS

b. Parallel – tube cooler

Figure 3. Conceptual cooler designs for organic module.


HOT GAS IN
COOLING WATER OUT
COOLING WATER IN
COOL GAS OUT

c. Thin — film cooler.

Figure 3. Concluded.

TABLE 1. COMPARISON OF GAS COOLER CONCEPTS

Design	Advantages	Disadvantages
Coil	Easy to construct. Relatively inexpensive. Low gas pressure drop. Capable of adequate cooling with metallic construction, but not glass.	Very difficult to clean. Must be large and bulky to achieve necessary heat transistor.
Parallel Tubes	Low gas pressure drop. Capable of adequate cooling with metallic construction, but not with glass. Compact.	Moderately difficult to clean. Complex design. Relatively costly.
Thin Film	Cleaning very easy. All surfaces accessible. Low pressure drop. Small, compact. Capable of adequate cooling with either metallic or glass construction.	Somewhat more expensive than the coil. Cheaper than the parallel tube design.

module design was to allow a combination of the gas cooling and sorption functions into a simpler unit. Figure 4 shows schematically the organic module functions at the start of the project, and after the change.

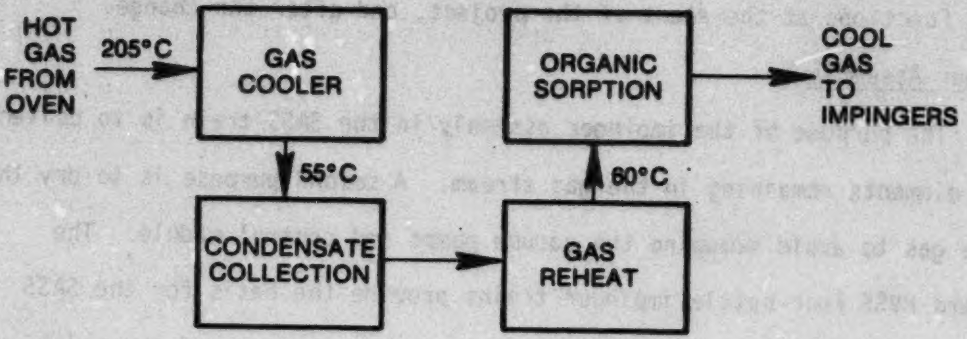
Impinger Assembly

The purpose of the impinger assembly in the SASS train is to collect trace elements remaining in the gas stream. A second purpose is to dry the sample gas to avoid damaging the vacuum pumps and control module. The standard HVSS four-bottle impinger trains provide the basis for the SASS impinger design, with one important modification. Because of the relatively high pressure drop in several of the SASS components, the impinger assembly operates at a substantial vacuum (10 to 20 inches Hg). The actual volumetric flowrate in the impingers is as high as 12 acfm, leading to excessive splashing of the impinger solutions and possible solution carryover. In order to eliminate this problem, special oversized glass impinger bottles are required.

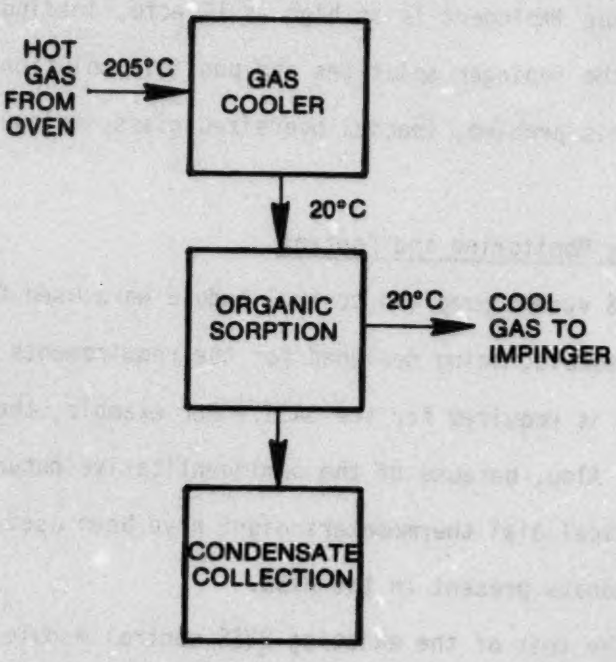
Gas Flow and Temperature Monitoring and Control

The standard HVSS vacuum pump and control module were used for the SASS. The HVSS control module, being designed for the requirements of Method 5, is more complex than is required for the SASS. For example, the dry gas meter is not required. Also, because of the semiquantitative nature of the mechanical SASS, mechanical dial thermometers might have been used instead of the thermocouple readouts present on the HVSS.

An analysis of the cost of the existing HVSS control module compared to the cost of redesigning a simpler control system was needed to make a final decision, along with consideration of such intangible factors as convenience and the desirability of HVSS-SASS component interchangeability.


HOT GAS FROM OVEN
205°C
GAS COOLER
55°C
CONDENSATE COLLECTION
GAS REHEAT
60°C
ORGANIC SORPTION
COOL GAS TO IMPINGERS

a. Original organic module function.


HOT GAS FROM OVEN
205°C
GAS COOLER
20°C
ORGANIC SORPTION
20°C
COOL GAS TO IMPINGER
CONDENSATE COLLECTION

b. Revised organic module function.

Figure 4. Organic module functional schematic diagrams.

3.4 CONCEPTUAL DESIGN STUDY

A wide range of hardware configurations could be provided within the constraints imposed by the basic design philosophy. An early task in the SASS development program was the preparation of a Conceptual Design Study. The purpose of the study was to postulate several SASS designs covering a range of costs and capabilities, and then do a detailed cost-benefit analysis on each. One of the designs was then recommended to EPA, who made the final decision.

The Conceptual Design Study was submitted to EPA as an internal study report in April 1976. Since the study was not available in the open literature, it has been reproduced in Appendix C. It should be remembered that costs are in early 1976 dollars.

On the basis of the Conceptual Design Study, EPA concurred with the recommendation and accepted Option B as the basis for SASS train development. Upon receipt of EPA approval, work was immediately begun on the formal design, construction, and testing of the SASS.

SECTION 4

SASS DETAILED DESIGN AND CONSTRUCTION

Official notice was received from EPA on July 19, 1976, to proceed with the detailed design, construction, and testing of three SASS units based on Design B of the Conceptual Design Study. A design effort was immediately begun which led to construction of the first SASS trains. Although some changes and modifications were made subsequently, the first trains are substantially the same as current models.

Figure 5 shows a photograph of a SASS, and Figure 6 presents a schematic diagram. These figures show a current (mid-1977) SASS, but could equally well represent the first SASS trains, although the first trains had one rather than two vacuum pumps (SASS changes and modifications are discussed in Section 6). The operation of the SASS is shown in Figure 6. This figure shows the progression of the sample gas through the extractive probe, the cyclones and filter, the organic module, the impinger/trace element collector, the vacuum pump(s), and the control module.

In this section we discuss the design of each SASS component.

4.1 HEATED PROBE

The SASS probe extracts gas/particulate samples from the source being tested, monitors the temperature and gas velocity of the source, and maintains sample temperatures above the condensation point of water/SO_3 mixtures. Since the SASS is designed to operate at a sampling rate four to five

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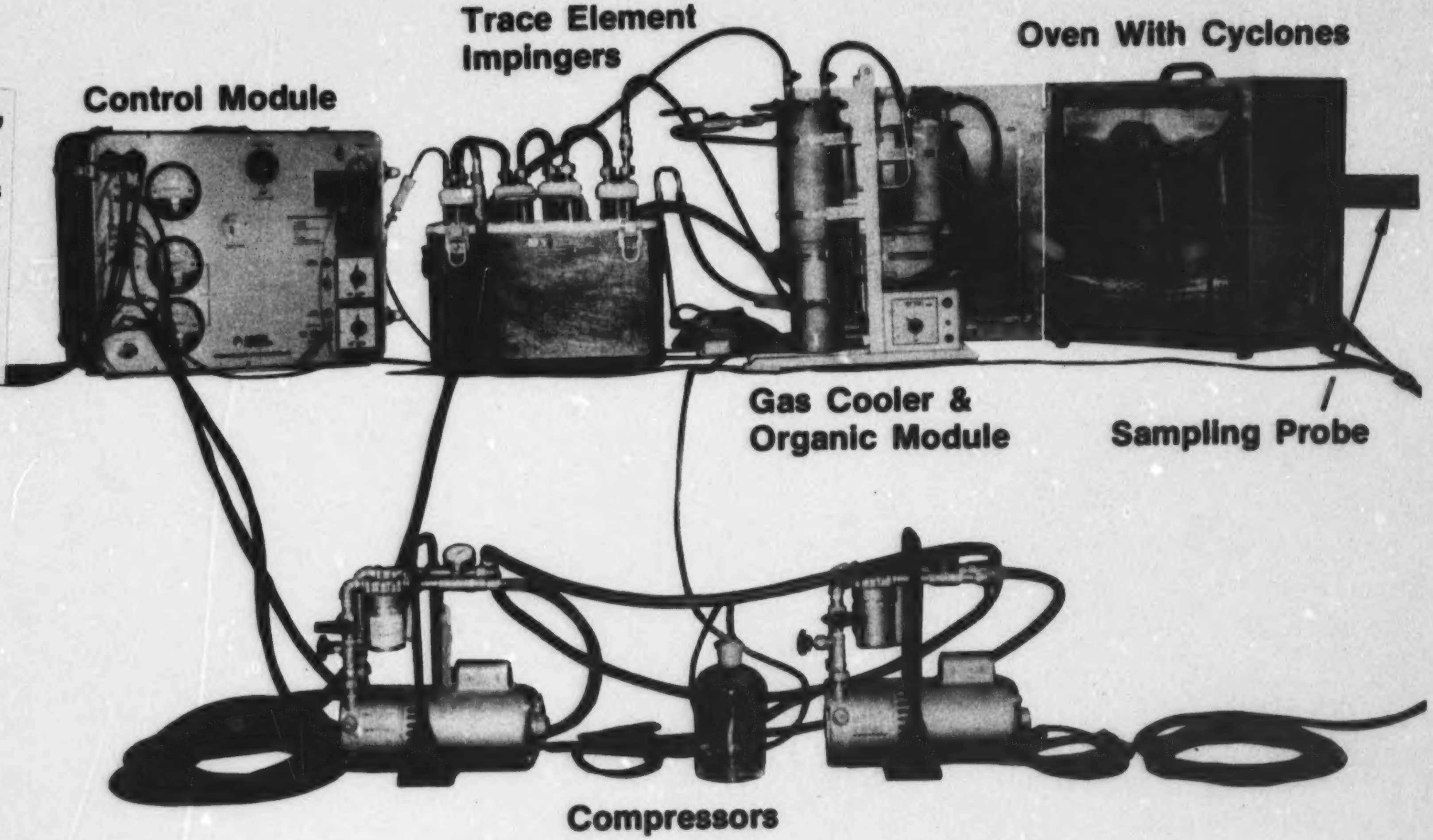
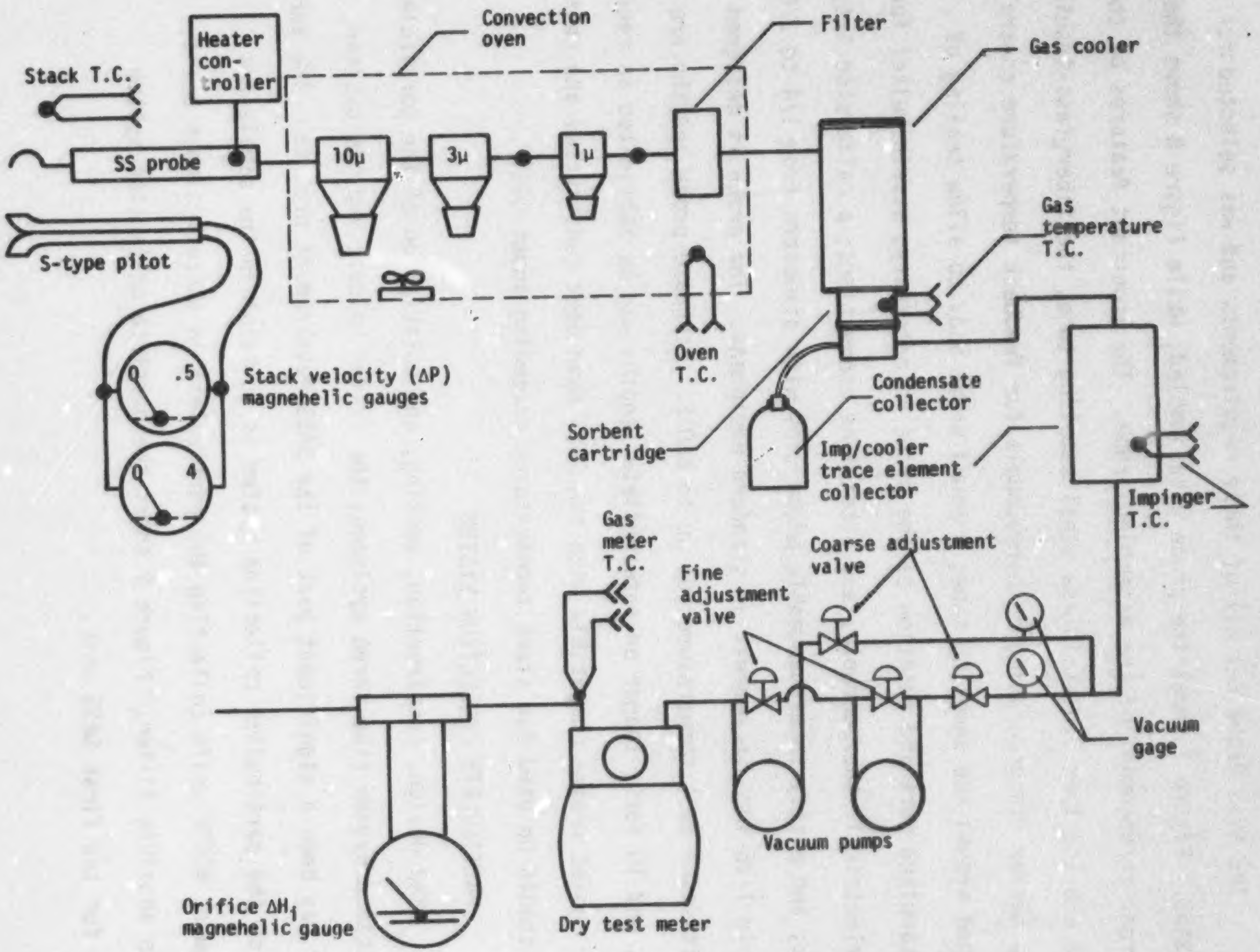

Trace Element Impingers
Oven With Cyclones
Control Module
Gas Cooler & Organic Module
Sampling Probe
Compressors

Figure 5. Source assessment sampling system (SASS).



Convection oven
Filter
Gas cooler
Heater con-troller
Stack T.C.
SS probe
10μ
3μ
1μ
S-type pitot
Gas temperature T.C.
Oven T.C.
Condensate collector
0
.5
0
4
Stack velocity (ΔP) magnehelic gauges
Sorbent cartridge
Imp/cooler trace element collector
Impinger T.C.
Gas meter T.C.
Fine adjustment valve
Coarse adjustment valve
Vacuum gage
Vacuum pumps
Orifice ΔH_i magnehelic gauge
Dry test meter

Figure 6. Schematic of SASS.

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times higher than conventional Method 5 sampling equipment, the SASS probe must be adaptable to this high flowrate.

The HVSS Probe met all of these requirements and was selected for the SASS. Figure 7 shows the probe disassembled, while Figure 8 shows the internal arrangement of the assembled probe. The important features of the probe are the Type 316 stainless steel sampling tube; the fiberglass-insulated strip heater (incorporating a thermocouple for feedback temperature control) wrapped around the sampling tube; a round probe body to allow sealing of the sampling port and rotation of the probe as necessary; strain relief for all electrical, thermocouple, and pitot line connections; a calibrated S-type pitot; and easily interchangeable probe tips with diameters from 1/4 to 3/4 inch in 1/16-inch increments as standard equipment. The probe is designed to withstand duct temperatures of up to 600°F. Standard probe lengths are 3, 5, and 10 feet; longer or intermediate lengths can be fabricated as required. Water cooled probes compatible with the SASS have been constructed and tested. They should be used for stack temperatures exceeding about 500°F.

4.2 PARTICULATE COLLECTION SYSTEM

The design, construction, testing, and calibration of the particulate collection system (the three cyclones, the filter holder, and the cyclone oven) has been a significant part of the SASS development program. The purpose of the particulate collection system is to maintain the sample gas stream at 400°F while collecting the particulate in three cyclones and a backup absolute filter. Figure 9 shows the particle collection system built for the first SASS unit.

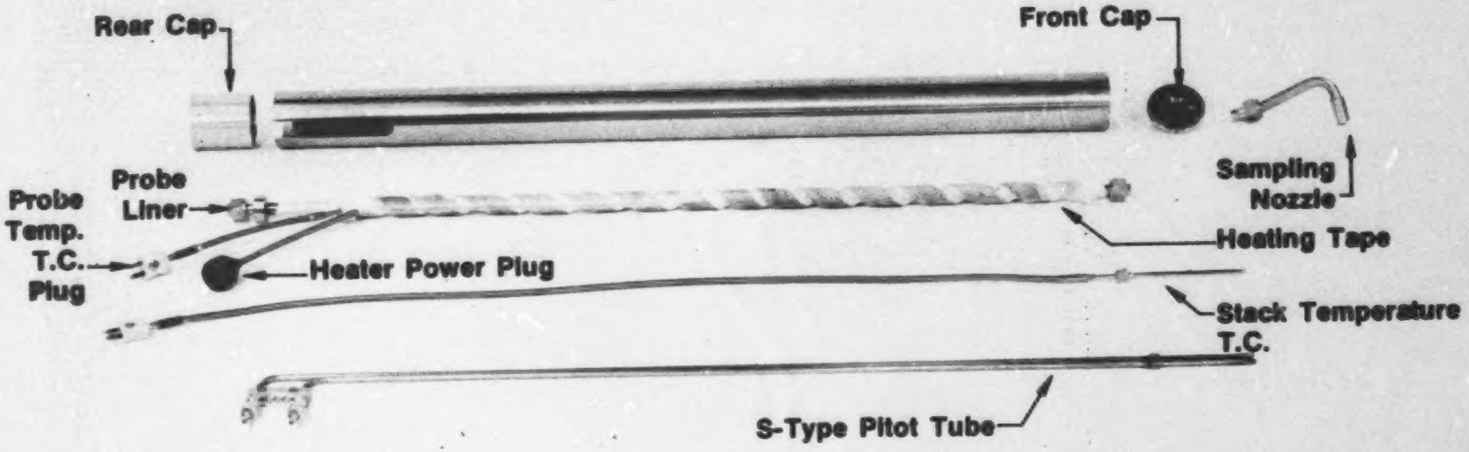
Rear Cap
Front Cap
Sampling Nozzle
Probe Liner
Probe Temp. T.C. Plug
Heater Power Plug
Heating Tape
Stack Temperature T.C.
S-Type Pitot Tube

Figure 7. Heated probe.

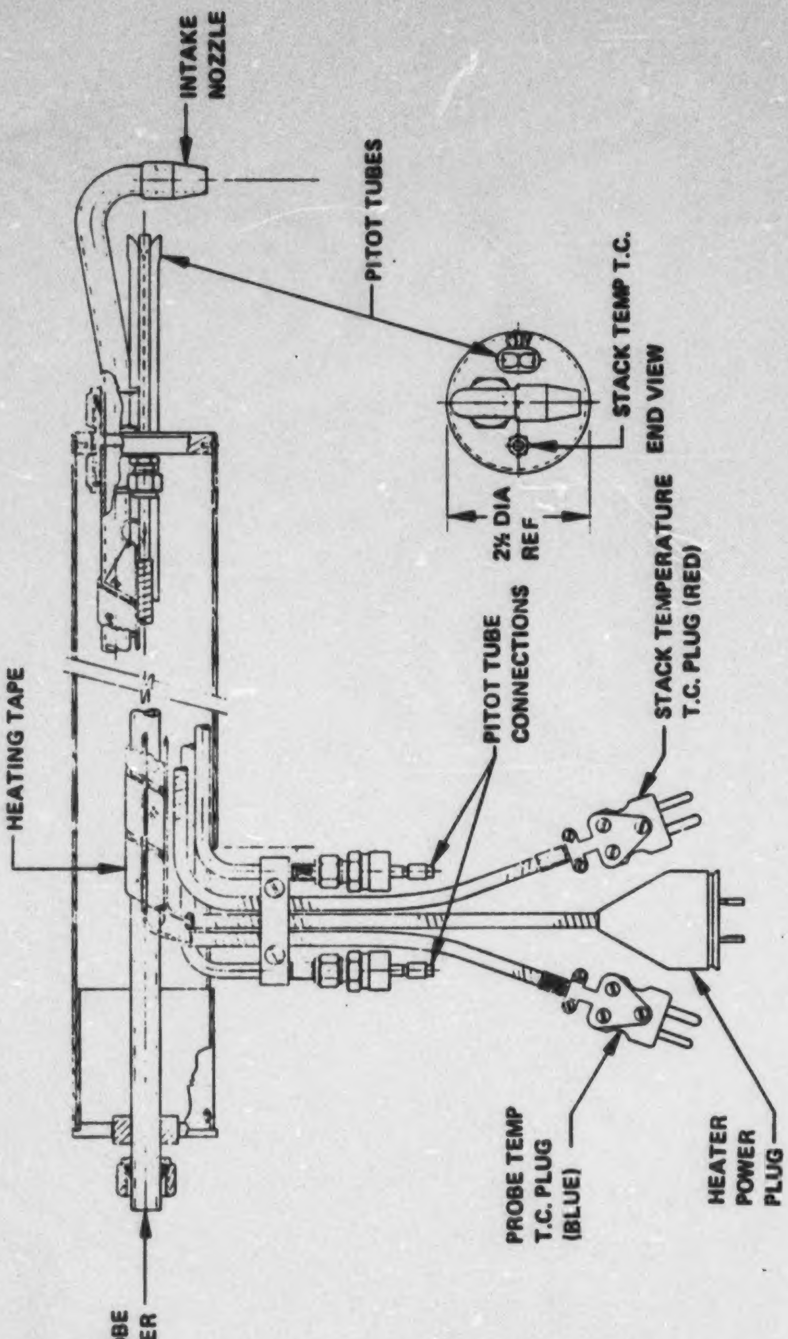
INTAKE NOZZLE
PITOT TUBES
STACK TEMP T.C.
END VIEW
2½ DIA REF
HEATING TAPE
PITOT TUBE CONNECTIONS
STACK TEMPERATURE T.C. PLUG (RED)
PROBE TEMP T.C. PLUG (BLUE)
HEATER POWER PLUG
PROBE LINER

Figure 8. Probe details.

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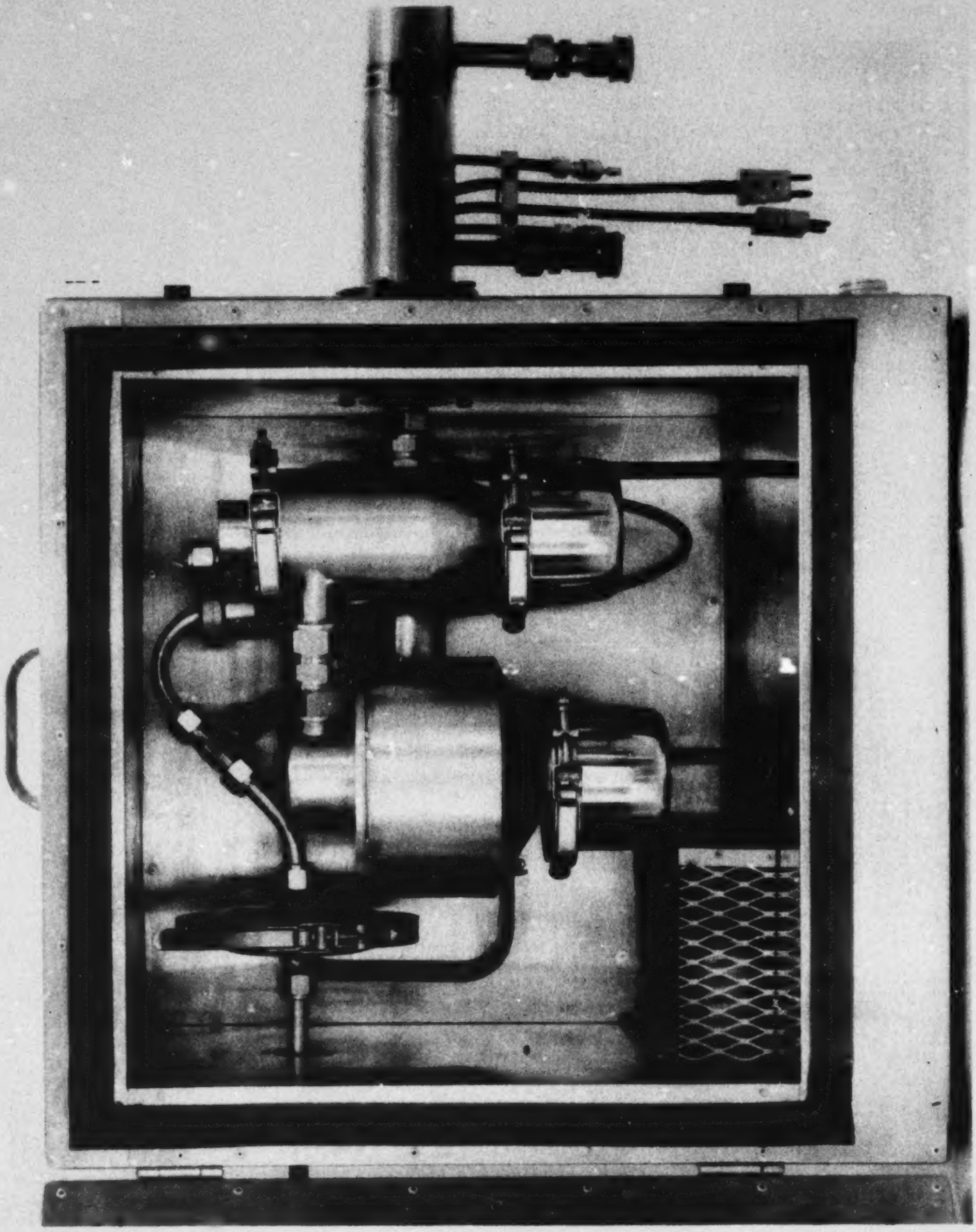

Figure 9. Cyclone train and filter with oven.

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4.2.1 The Cyclones

The SASS cyclone assembly is patterned closely on the cyclone design developed by Aerotherm and Southern Research Institute for the Combustion Power Sampler (see Section 2). Some changes from that design were made to increase the ease of working with the cyclones in the field, but the size and performance of the cyclones were essentially unchanged. Figure 10 schematically illustrates the three SASS cyclones and shows key dimensions of each.

In keeping with the basic design philosophy, the cyclone assembly was to be designed entirely of 316 stainless steel and Teflon. It was to be lightweight and compact for easy field use, and easily assembled, disassembled, and cleaned in the field. These requirements imposed limitations on the physical arrangement of the cyclones and their method of construction.

After considering several possible cyclone fabrication methods -- rolling and welding of flat platestock, spinning maching from billets, and deep-drawing from sheet stock -- spinning was chosen. Spinning is the best way to produce cyclones with thin walls for light weight with good dimensional tolerance and durability. The cyclone bodies are manufactured from Type 316 tubestock by rapidly spinning the tube axially while forcing the tube into a mold using a stationary hot mandrel. Top and bottom flanges and inlet and outlet tubes are machined and welded to the spun bodies. All welding is performed in an inert helium atmosphere with a 316 welding rod, and welded parts are later vacuum annealed to eliminate retained strain in the weld areas.

To reduce the overall size of the cyclone assembly, the cyclones and backup filter must be closely packed. Figure 11 shows a top view of the

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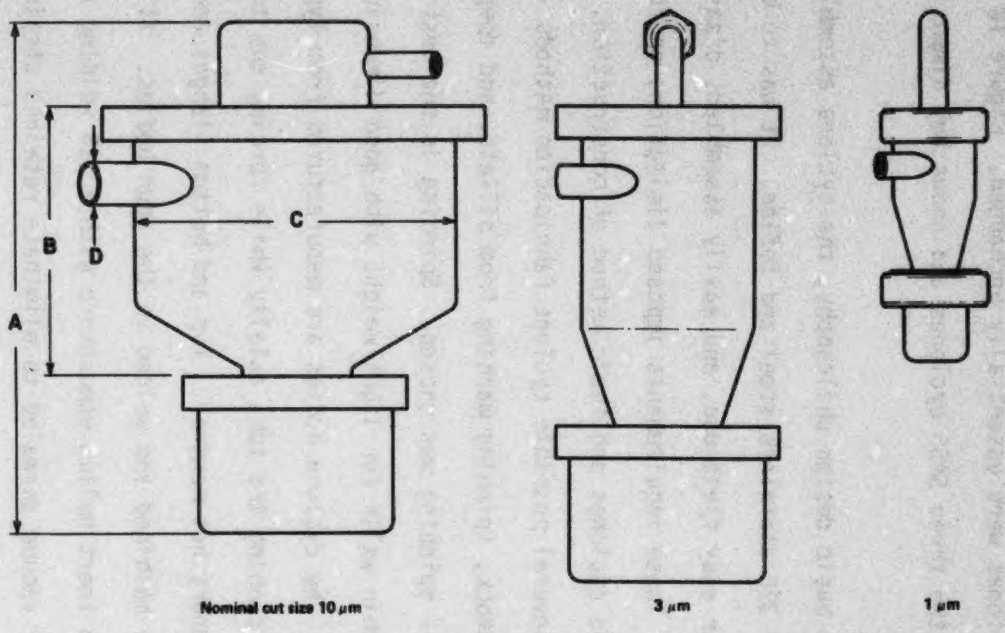
A
B
C
D
Nominal cut size 10 µm
3 µm
1 µm

	Dimensions			
Cyclone	Total Height A, cm	Body Height B, cm	Body Diameter C, cm	Inlet ID D, cm
10 µm	26.0	13.2	15.2	5.1
3 µm	27.1	15.2	8.1	1.8
1 µm	16.5	7.8	3.7	0.9

Figure 10. SASS cyclone dimensions.

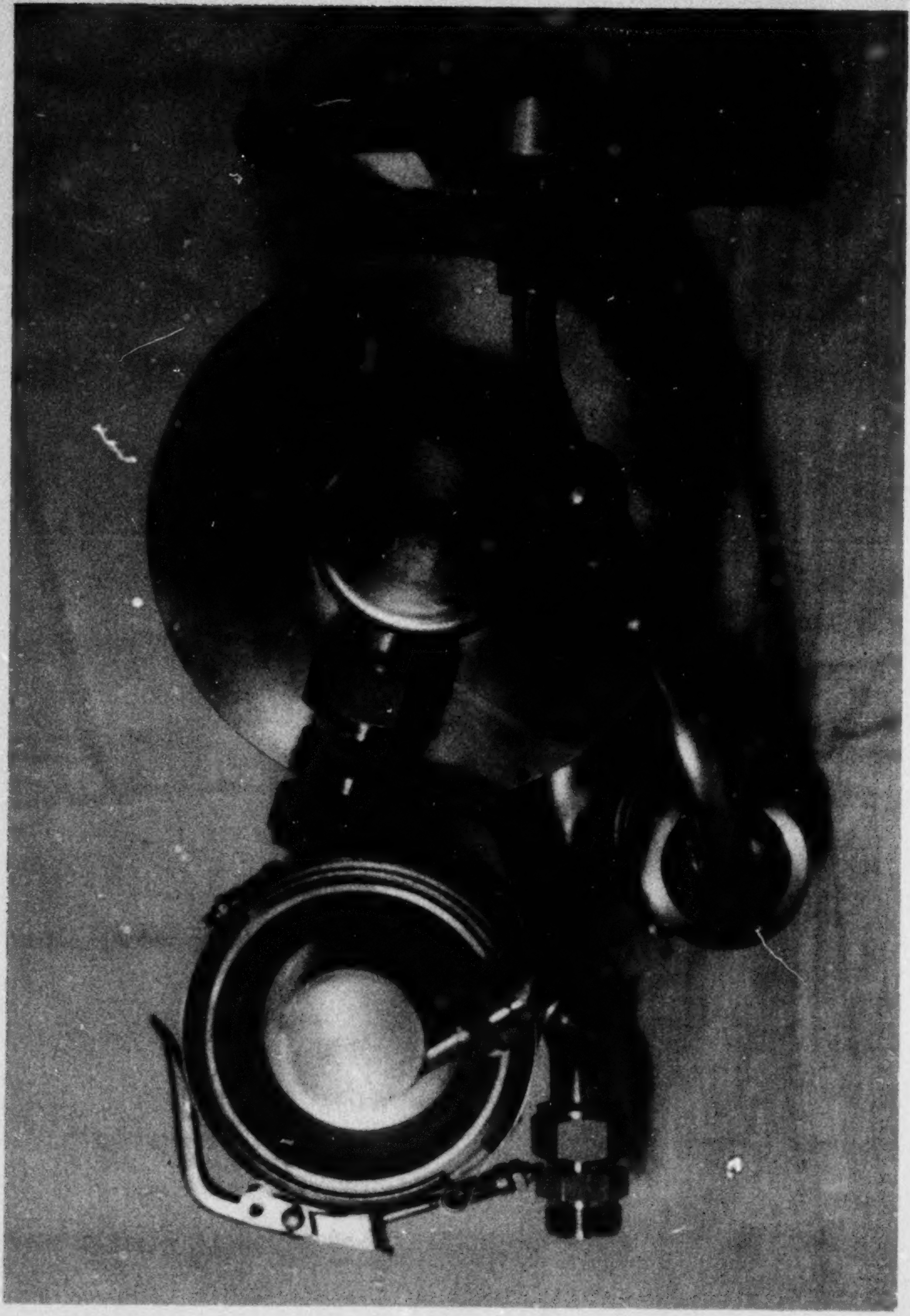

Figure 11. Top view of SASS cyclones.

first SASS cyclone assembly. Considerable care was taken to arrange the connecting tubing so the cyclones were nestled together closely, yet with minimum lengths of connecting tubing between cyclones, and no sharp bends in the tubing. Minimizing tubing length and bending reduces particulate deposition in the tubes.

Figure 12 and 13 show details of the individual cyclones. Several points may be noted. Comparing Figures 11 and 12, it is seen that the method of attaching the top flange to the body of the large cyclone has been changed. In Figure 11, the top flange is attached by screws, while in Figure 12, the flange is attached with an aircraft clamp. The screw attachment method was used only in the first prototype cyclone assembly. Clamps were used in subsequent SASS units and have proven to be convenient and reliable for field use.

The sealing gasket and O-ring shown in Figures 12 and 13 are white Teflon. These Teflon seals proved to be troublesome because of their noncompliance and tendancy to cold-flow, leading to difficulty in getting satisfactory leak tests. As described in Section 6, Viton seals were specified for the SASS in June 1977.

4.2.2 The Filter Holder

The filter holder houses and supports an absolute backup filter for the series cyclones. Since the filter is likely to require frequent replacement when sampling in streams with high particulate loading (1 grain/standard cubic foot or higher), it is desirable that the filter be easily changed during a test. The HVSS filter holder met these requirements, except for the materials for construction (it is made of Type 304 stainless steel). Figure 14 shows a SASS filter housing assembly; it is dimensionally

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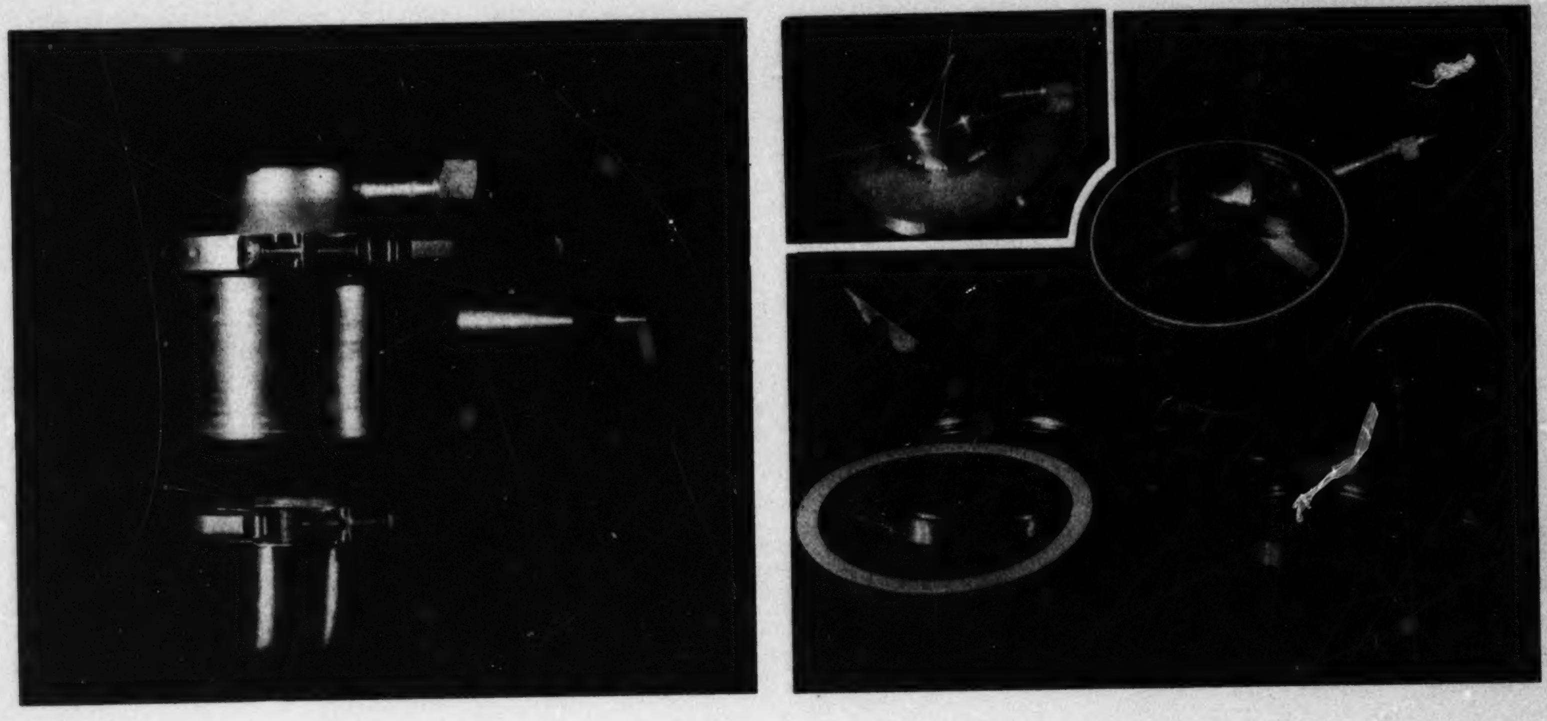

10-µm cyclone

10-µm cyclone breakdown

Figure 12. 10-µm cyclone assembly.

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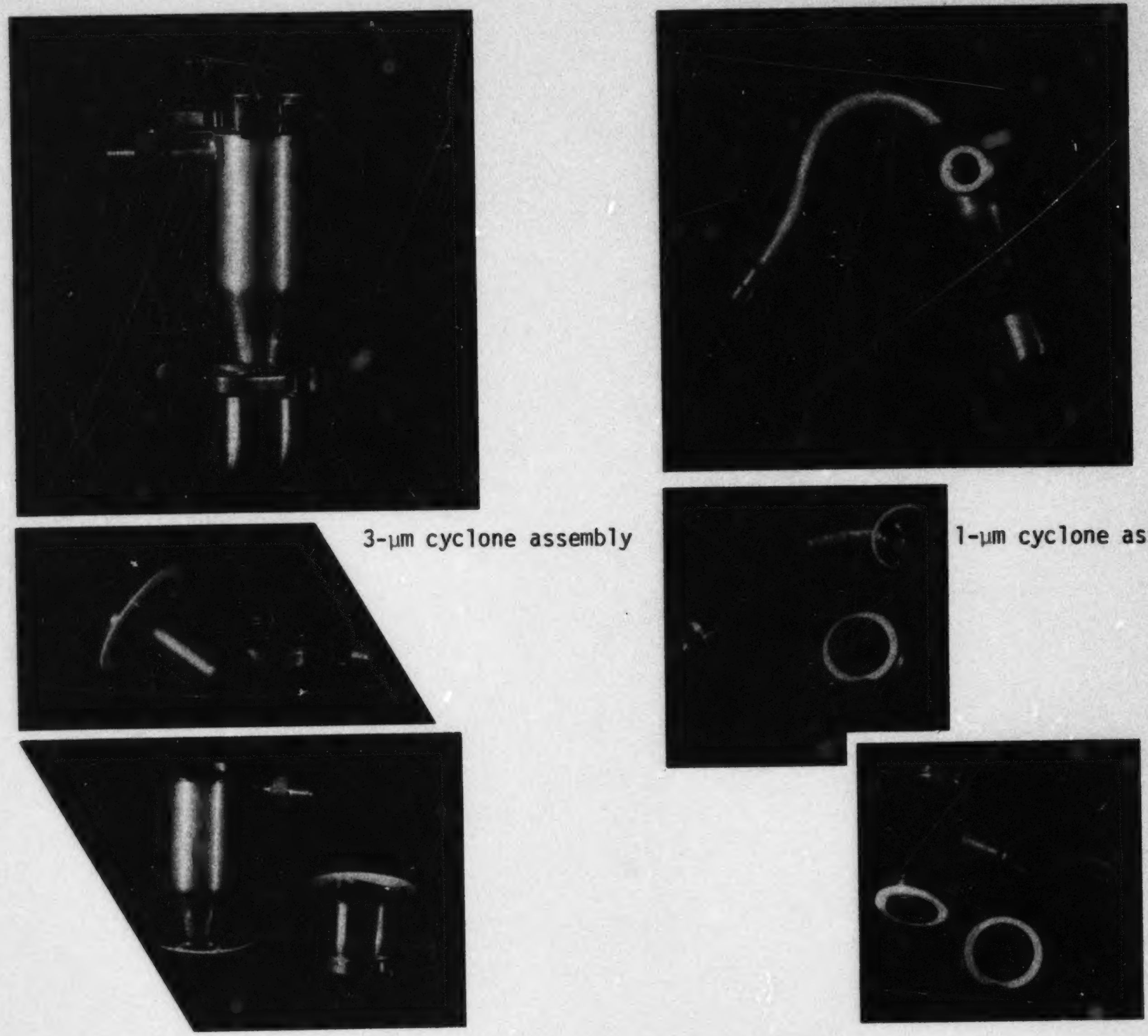
6



3-µm cyclone assembly

1-µm cyclone assembly

Figure 13. Small and medium cyclone assembly.

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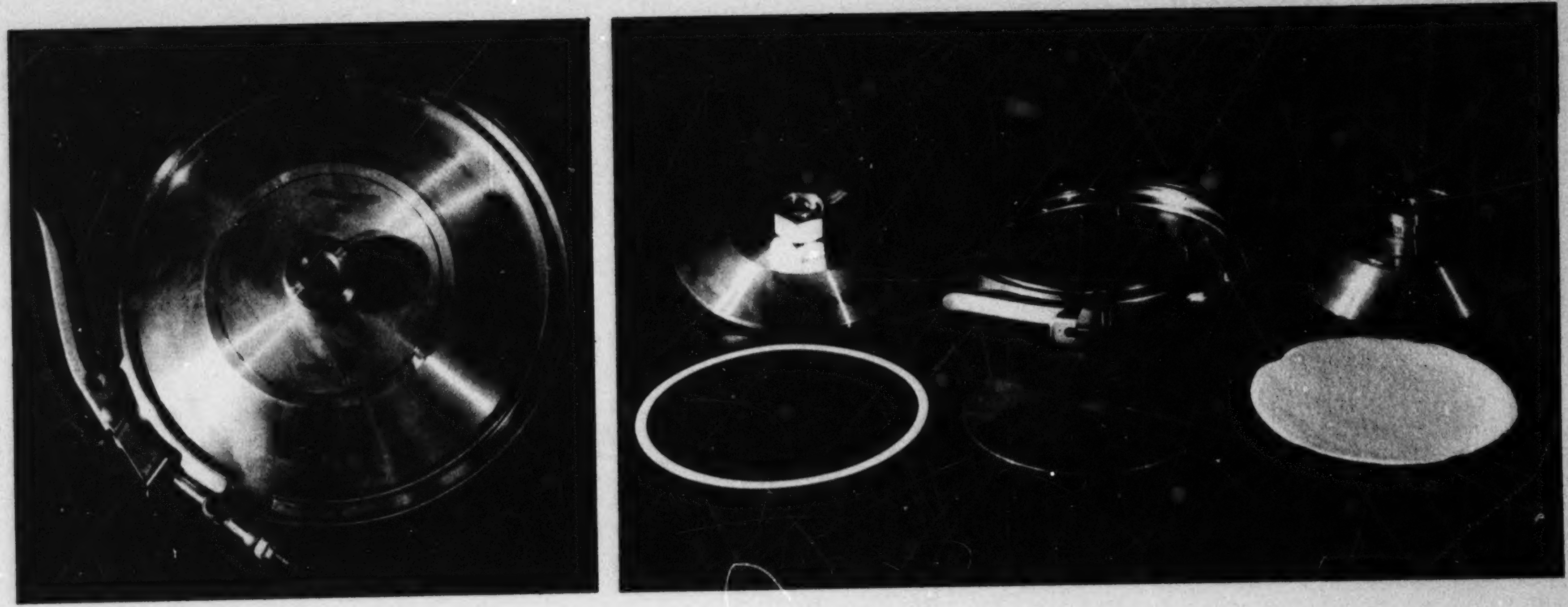

Figure 14. Filter housing assembly.

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equivalent to the HVSS filter housing, but is machined from type 316 stainless steel. The figure shows Teflon seals; Viton-A seals were later substituted.

4.2.3 The Cyclone Oven

The oven provides a constant temperature environment for the cyclones and filter, as well as mechanical protection. It also supports the probe by means of a collar attached to the side of the oven, which securely clamps the probe. The probe and oven collar are so designed that the probe can be rotated to any angular position, as shown in Figure 15.

The SASS cyclone oven is a sturdy, double-walled box with a stainless steel liner, 2 inches of fiberglass insulation and a lightweight aluminum outer shell. The exterior of the oven is safe to touch even when the interior has been heated to 400°F. Figures 5 and 9 show the configuration of the cyclone oven.

The maximum power dissipation of the single-sheathed heating element is 1200 watts, sufficient to bring the oven to 400°F in less than 15 minutes. A fan circulates the heat to the cyclones and filter, so that these too are heated within 15 minutes. The fan may also be used to hasten cooling when the heater is off and the oven door is left open. The temperature in the oven during a test is normally maintained at 400° ± 5°F by means of a temperature controller located in the control module. A temperature of 500°F can easily be achieved but, to protect the silicone rubber gaskets on the door jamb, it is recommended that the oven not be operated beyond 450°F. Level 1 procedure requires the oven temperature to be maintained at 400°F.

4.3 ORGANIC MODULE

The sample gas leaves the filter holder at 400°F, cleaned of particulate but still containing any organic vapors or trace element vapors that are present. The organic module cools the gas stream, and passes the cooled gas

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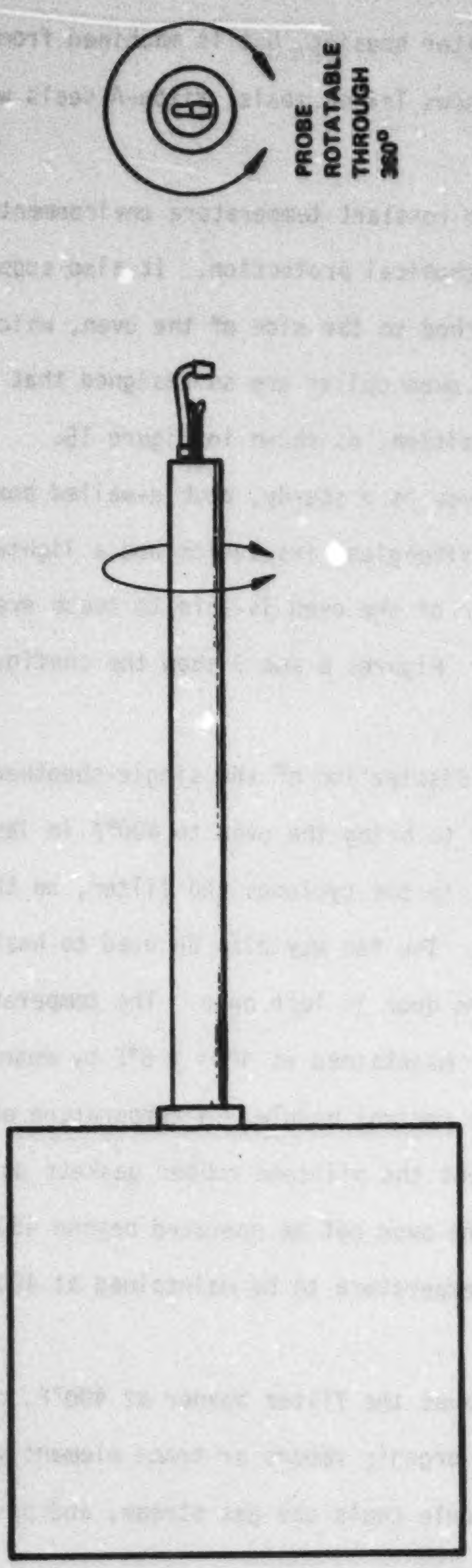
PROBE
ROTATABLE
THROUGH
360°

Figure 15. Rotation of sampling probe.

and any condensate through an absorbent bed. The bed will collect organic species of less than some characteristic volatility, as well as some fraction of the metallic trace elements present.

As discussed in Section 3, several design concepts were considered for the organic module. The concept finally chosen uses a thin-film heat exchanger, vertically oriented, with the sorbent bed located at the base of the cooling section. Precise temperature control of the sorbent bed was deemed essential for reproducible organic species collection. Accordingly, the organic module temperature control system is designed with the ability to either heat or cool the sample gas stream to maintain the sorbent bed at its operating temperature of 20°C ± 1°C.

Figure 16 is a schematic illustration of the organic module. The left half of the apparatus shown in Figure 16 is the operating part, with the right side devoted to temperature maintenance and control. Figure 17 shows an exploded view of the left (active) side of organic module. Figure 18 shows a photograph of an organic module. Referring to Figure 17, the hot sample gas from the cyclone oven enters the organic module at top left. The hot gas passes down the thin (about 0.040-inch gap) annular space between the gas cooler inner wall and the gas cooler outer wall. Both the inner and outer walls are actively cooled (the cutaway view in Figure 16 clearly shows the coolant liquid flow passages).

The inner wall of the gas cooler section is cooled by the continuous flow of cold (~40°F) water from a pump located in the ice water-filled impinger assembly case. The inner wall provides about 70 percent of the cooling necessary to reduce the sample gas stream from 400°F to 68°F (20°C). The remaining cooling is provided the water-jacketed outer cooler wall. This outer water

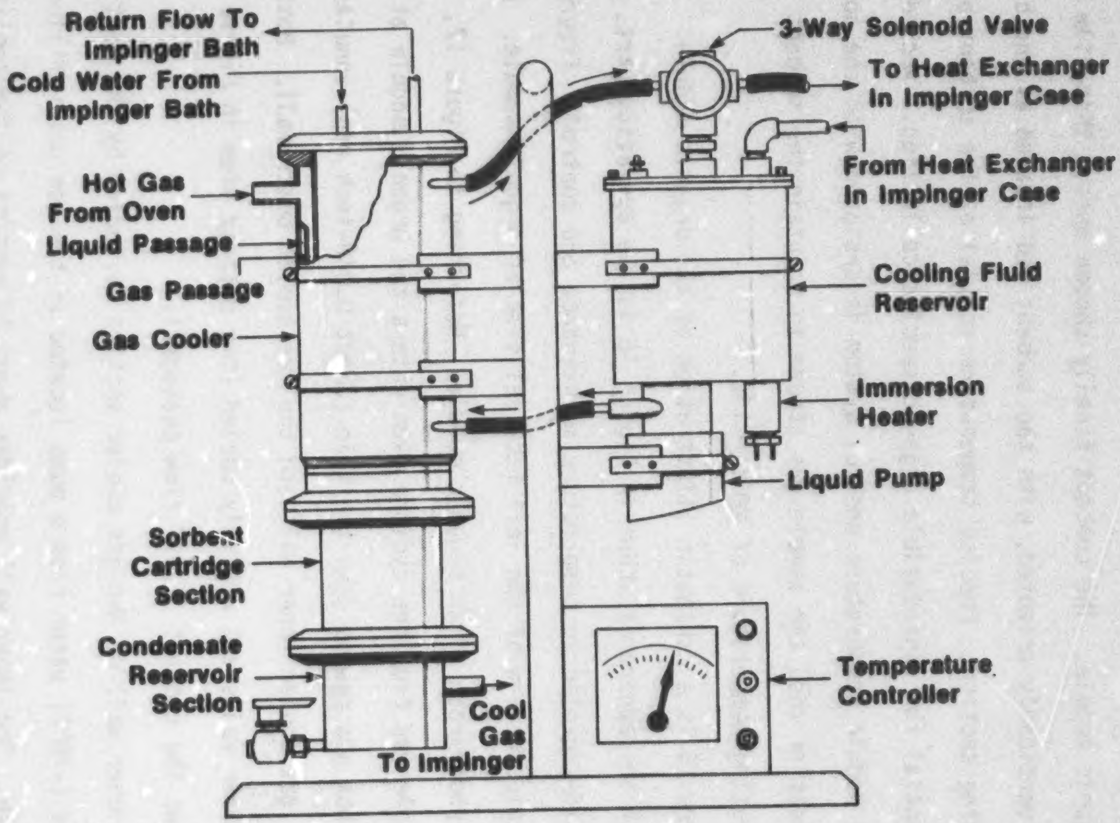
Return Flow To Impinger Bath
Cold Water From Impinger Bath
Hot Gas From Oven
Liquid Passage
Gas Passage
Gas Cooler
Sorbent Cartridge Section
Condensate Reservoir Section
Cool Gas To Impinger
3-Way Solenoid Valve
To Heat Exchanger In Impinger Case
From Heat Exchanger In Impinger Case
Cooling Fluid Reservoir
Immersion Heater
Liquid Pump
Temperature Controller

Figure 16. Organic module schematic.

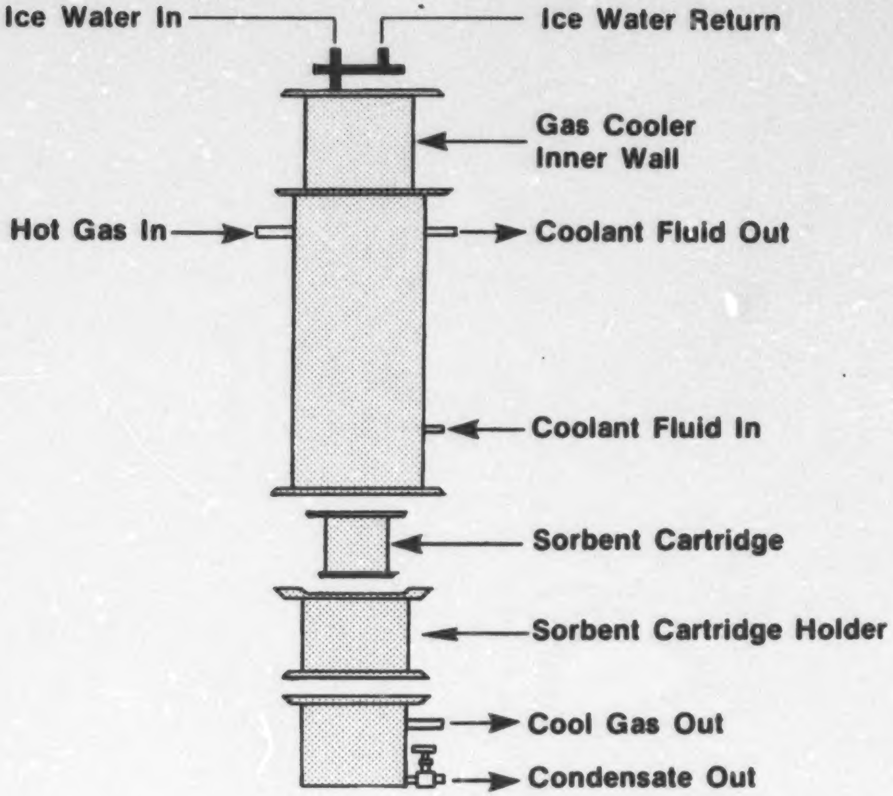
Ice Water In
Ice Water Return
Gas Cooler Inner Wall
Hot Gas In
Coolant Fluid Out
Coolant Fluid In
Sorbent Cartridge
Sorbent Cartridge Holder
Cool Gas Out
Condensate Out

Figure 17. Organic module — exploded view.

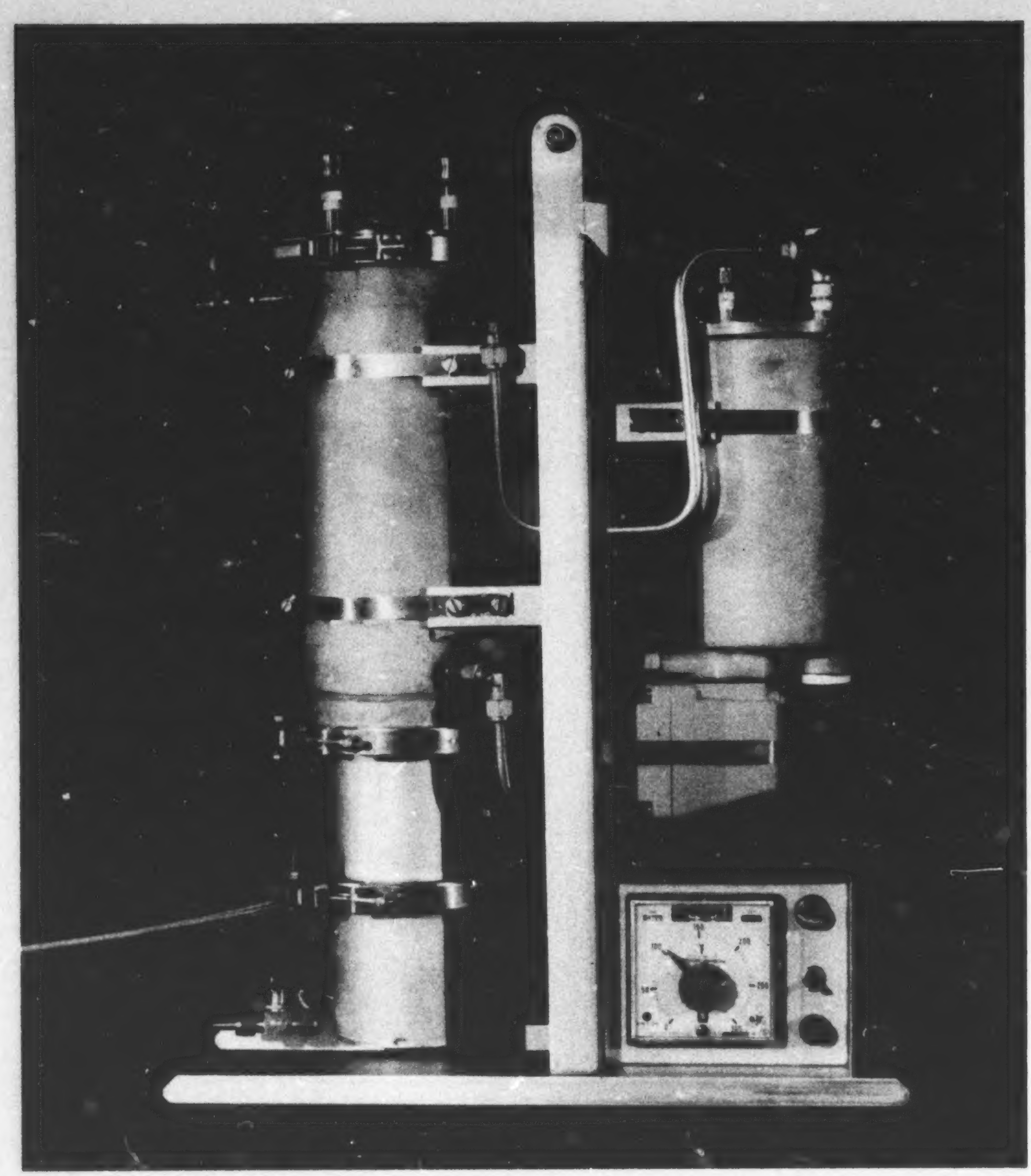

Figure 18. Organic module.

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jacket is directly connected by means of a small pump to the cooling fluid reservoir on the right side of the organic module (see Figure 16). The temperature of the cooling fluid reservoir can be adjusted either up or down to control the temperature of the gas cooler water jacket, and thus the sample gas. A dual-set-point temperature controller can energize a heating element to raise the temperature of the cooling fluid reservoir, or can switch the three-way solenoid valve at the top of the cooling fluid reservoir to dump heat to a heat exchanger in the impinger case (when the water jacket temperature must be reduced). This temperature control system can maintain the sample gas temperature just upstream of the sorbent cartridge at any temperature between about 15°C and 80°C. As previously mentioned, the standard operating temperature of the sorbent bed for Level 1 sampling is 20°C.

As the sample gas is cooled, water or acid will usually condense. The organic module is designed so that the cooled gas leaving the gas cooler section, along with any condensate formed, passes through the sorbent bed. The sorbent is typically a porous polymer gas chromatographic bed packing material (Rohm and Haas XAD-2 resin is currently specified for Level 1 sampling). It is contained in a sorbent cartridge, which is designed to be easily removed and replaced with an identical clean cartridge when several SASS tests are to be made sequentially.

Two types of sorbent cartridge are in use. Figure 19 shows the initial design, the one most commonly used. Two circular swatches of 316 stainless steel mesh are stretched and held over the ends of an open 316 stainless steel tube by two crimp rings, also of 316 stainless. The upper crimp ring incorporates a flange to support the sorbent cartridge and provides a seal so that condensate and gas pass through the sorbent material inside the cylinder.

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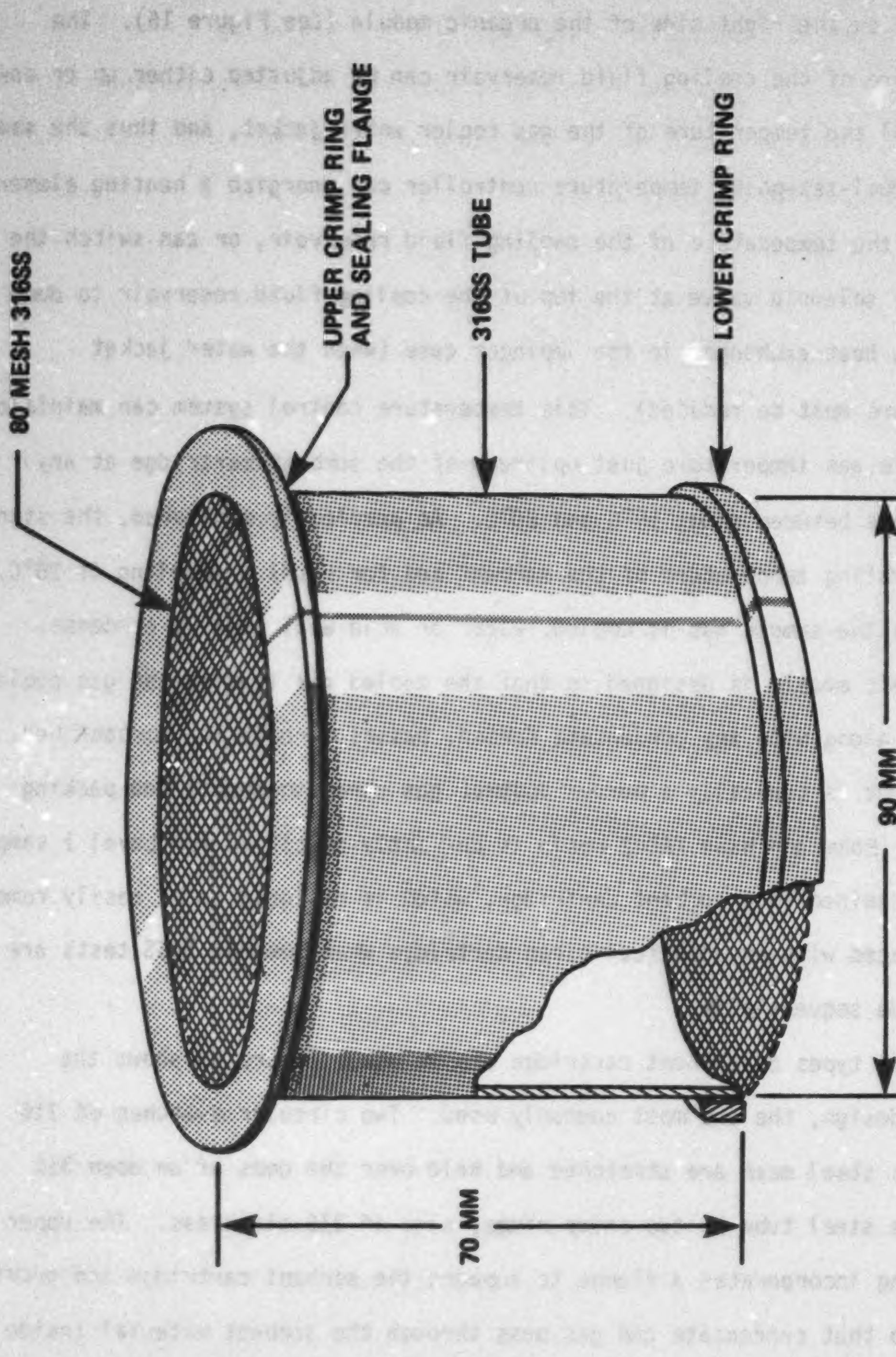
80 MESH 316SS
UPPER CRIMP RING AND SEALING FLANGE
316SS TUBE
LOWER CRIMP RING
90 MM
70 MM

Figure 19. Sorbent cartridge — original design.

Although this sorbent cartridge design was functionally satisfactory, some problems were encountered with removing and replacing the crimp rings in the field. A special clamp (Figure 20) was provided to remove and reinstall the crimp rings; however, use of the clamp was sometimes troublesome under the difficult conditions often prevailing at the sampling site. Several instances of broken or bent crimp rings were reported. Therefore, a modified sorbent cartridge was made available in mid-1977. Figure 21 shows the new design. The lower crimp ring has been replaced with a threaded cap nut that holds the lower screen in place. This makes it simple to remove and replace the sorbent by unscrewing the knurled cap. The top screen is still held in place with a crimp ring, since it should not be necessary to remove the top screen in the field. To make it easier to remove and replace the top crimp ring, the body of the sorbent cartridge has been made of thicker material, allowing a taper to be cut on the upper crimp ring mating surface. This allows the upper crimp ring to be removed and reinstalled with a soft hammer.

After the gas and condensate exit the lower screen of the sorbent cartridge, they pass into the condensate reservoir section (see Figure 16). Condensate collects in the bottom of the reservoir and is periodically pumped to a storage bottle; gas exits a tube at the top of the condensate reservoir section and passes to the impinger/trace element assembly. The organic module has been designed to be as simple and easy to use as possible. The active part of the organic module has been constructed in three separate sections, held together with aircraft snap-clamps. These clamps permit easy disassembly of the unit for sample recovery, cleanup, and ready access to any particular part of the unit. All of the parts of the organic module that

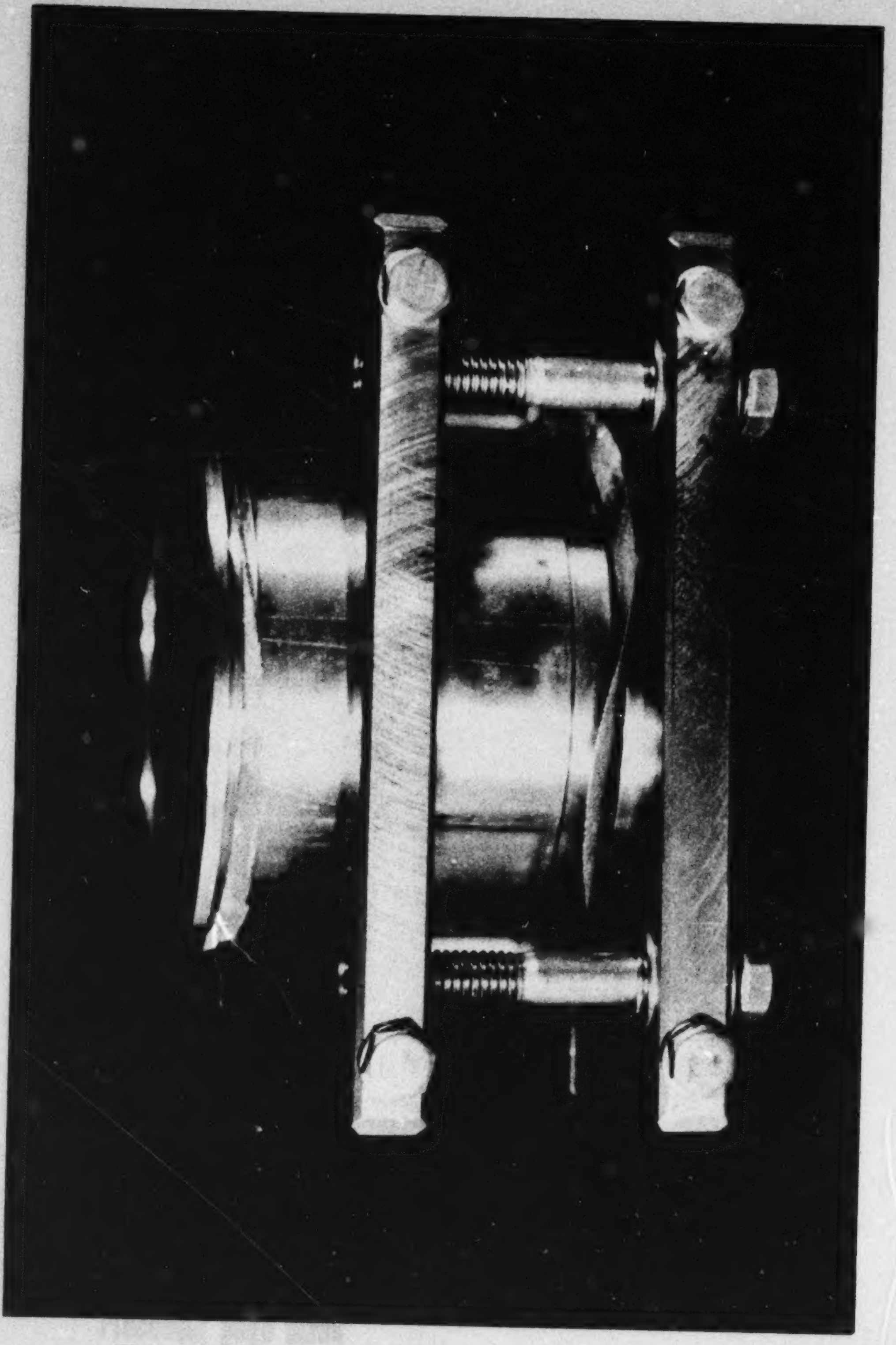

Figure 20. Sorbent cartridge assembly clamp.

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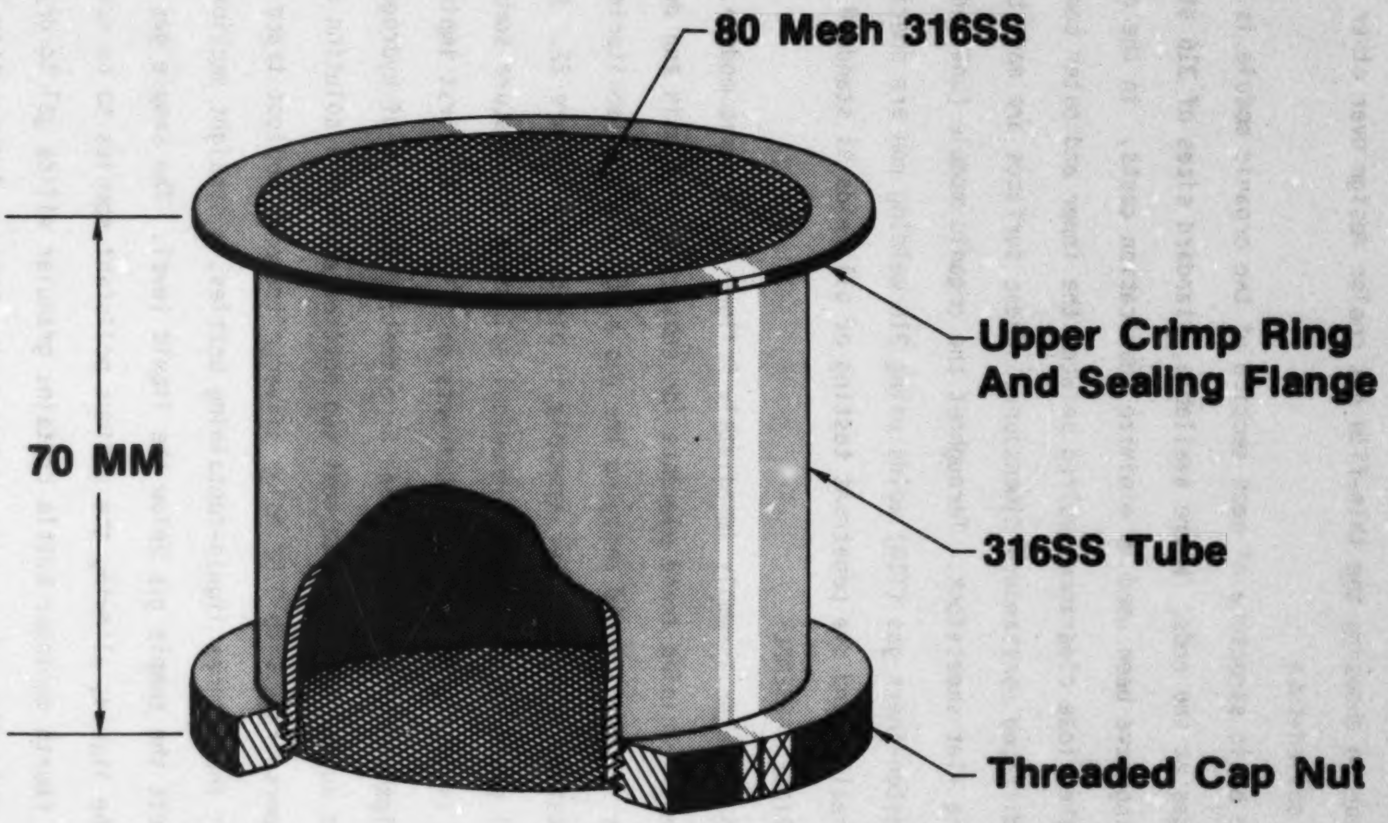
80 Mesh 316SS
Upper Crimp Ring And Sealing Flange
316SS Tube
Threaded Cap Nut
70 MM

Figure 21. Redesigned sorbent cartridge.

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contact the gas stream are smooth and easily accessible for cleaning -- a major factor in choosing the thin-film gas cooler design over other designs such as a coiled-tube.

The basic structure of each section of the organic module is a tube with flanges at the ends. Where available, standard sizes of 316 stainless steel tubing have been used to minimize fabrication costs. In the gas cooler section, the close clearance desired between the inner and outer cooling surfaces dictated nonstandard dimensions. These surfaces are made by rolling and welding flat sheetstock. Throughout the organic module (and the entire SASS) tungsten-inert gas (TIG) welds using 316 welding rod are specified. Vacuum annealing and dye penetrant testing of all welds is standard procedure.

4.4 IMPINGER ASSEMBLY

The impinger assembly immediately follows the organic module. It collects any remaining trace elements for subsequent analysis and dries the sample gas stream to avoid damaging the gas pumps and flow monitoring instrumentation. The impinger assembly is pictured in Figure 22. Four heavy wall glass bottles contain chemical solutions or moisture sorbent; 316 stainless steel and Teflon tubing directs gas flow. The first impinger bottle (on the right in Figure 22 contains an oxidative solution of hydrogen peroxide to collect sulfur oxides. The next two bottles contain a solution of 0.2 molar ammonium persulfate with 0.02 molar silver nitrate to collect trace elements. In each of these three liquid-containing bottles, a straight section of tubing ducts the sample gas below the liquid level. The sample gas bubbles through the liquid, allowing the various pollutant species to be scrubbed out. The fourth impinger bottle contains granular silica gel to dry the gas. In this bottle also, the gas is ducted to the bottom of the bottle by a stainless steel tube and flows upward through the silica gel granules.

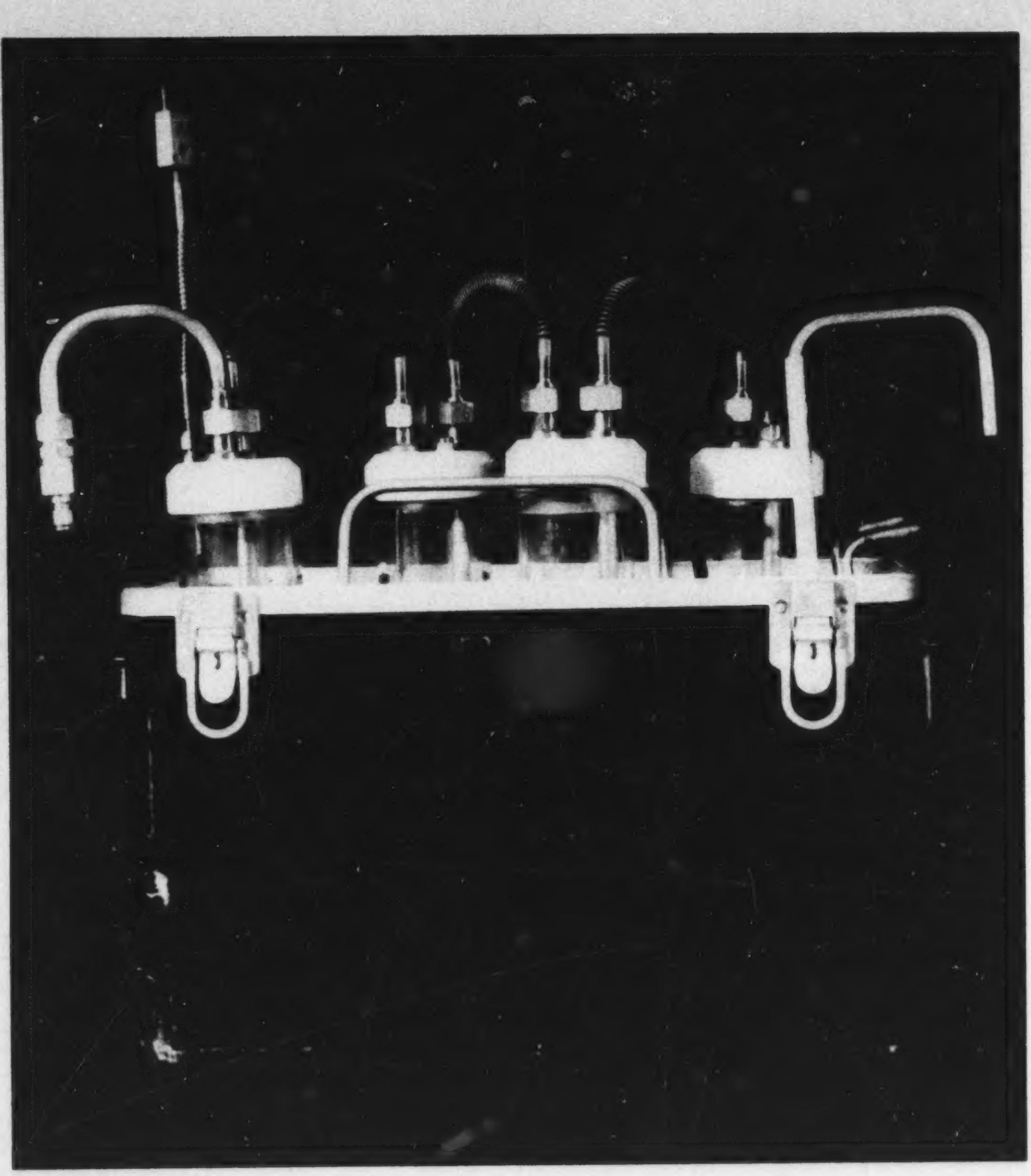

Figure 22. Impinger train out of case.

Several characteristics of the SASS led to design modifications from a standard high-volume impinger assembly. The most important characteristic was the large bottle volume required because of the high sample gas flowrate and the high vacuums that can exist at the impinger. Both of these factors tend to produce considerable splashing of the reagent liquids, with the possibility of liquid carryover to adjacent bottles. Figure 23 compares a standard impinger bottle (as used in the HVSS high volume Method 5 train) with the special bottle designed for the SASS. The SASS bottle, substantially larger, is designed with a wide base and relatively narrow neck to reduce the possibility of splashover. Also, the SASS bottle is constructed of heavy glass stock (about 1/4 inch thick) that is resistant to breakage.

The Teflon caps that seal the top of the glass bottles are standard HVSS parts, as are the gas tubes that convey the sample gas to the bottom of the bottles. The connecting tubes between the bottles, however, are specially designed for the SASS. In the initial SASS trains, the connecting tubing was of formed (rigid) 316 stainless steel tubing. Considerable difficulty was experienced with rigid connectors. When they were tightened down to be leak tight, the entire impinger assembly was held in a fixed position; any jostling or moving of the bottles tended to rotate a connector fitting, and caused leaks.

To eliminate this problem, and to make assembly and handling of the impinger assembly easier, flexible bellows-type connectors were installed in most SASS trains. Figure 24 shows an assembly drawing of the impinger train and includes some detail of the bellows connectors. Recently there have been reports of corrosion of the stainless steel bellows with sampling

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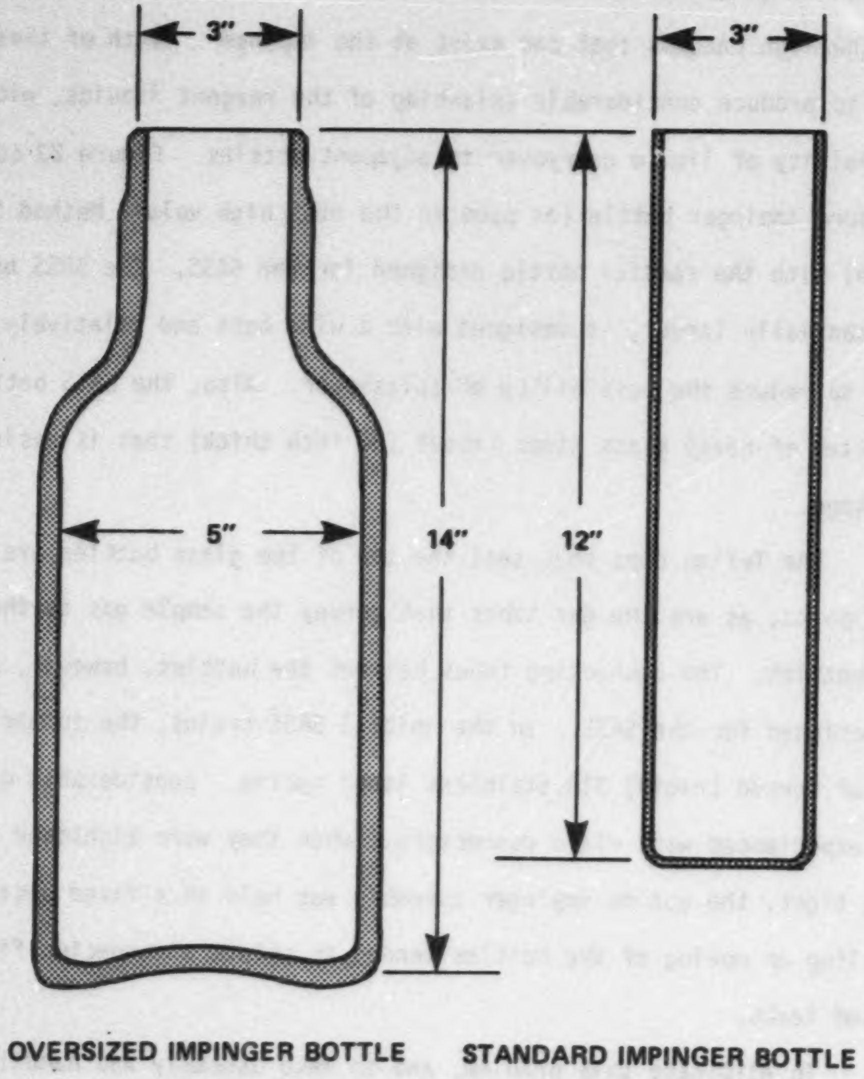
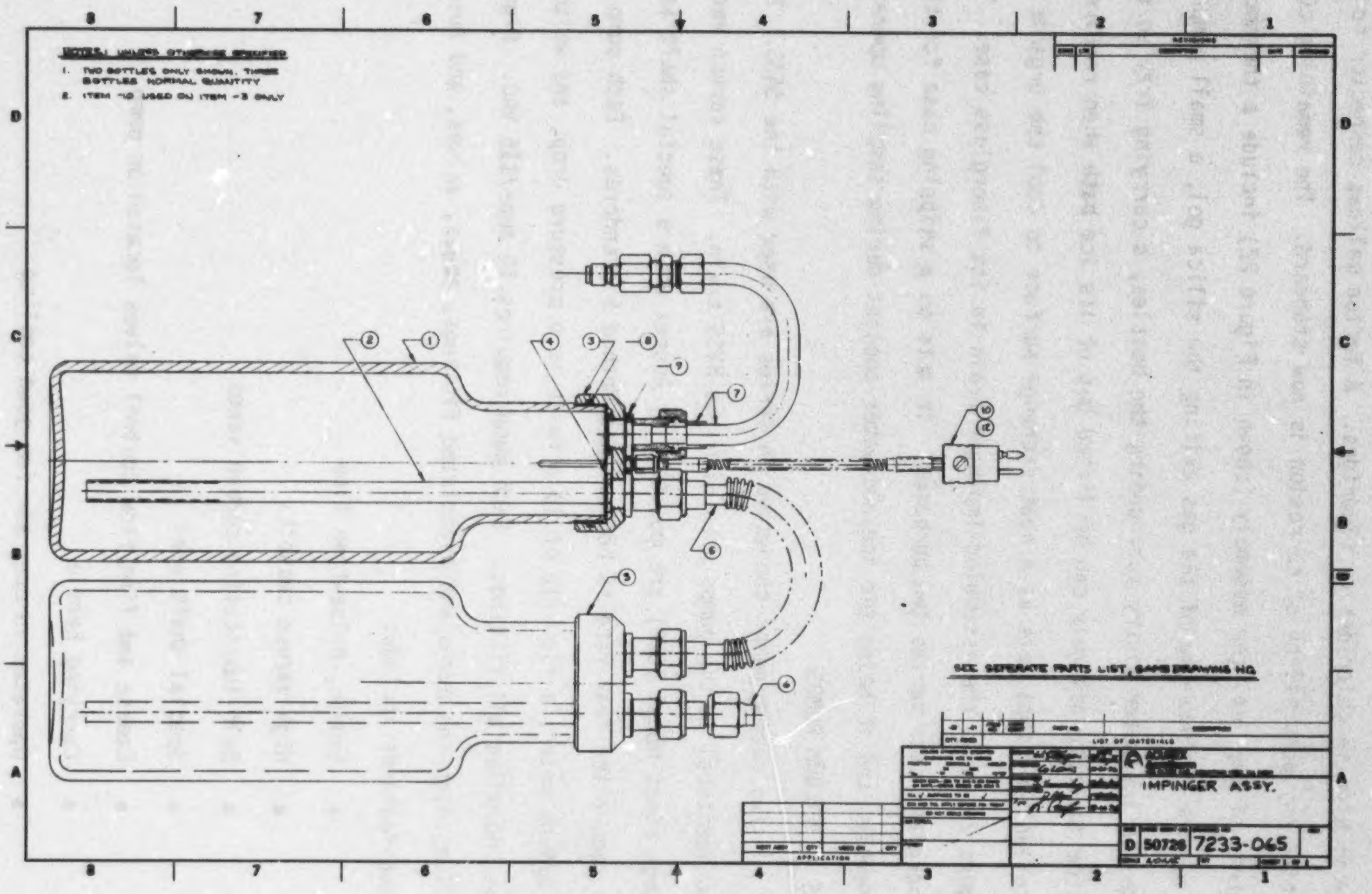

3"
3"
5"
14"
12"
OVERSIZED IMPINGER BOTTLE
STANDARD IMPINGER BOTTLE

Figure 23. Comparison of standard impinger bottle with SASS oversized bottle.



NOTES: UNLESS OTHERWISE SPECIFIED
1. TWO BOTTLES ONLY SHOWN, THREE BOTTLES NORMAL QUANTITY
2. ITEM 10 USED ON ITEM -3 ONLY
1
2
3
4
5
6
7
8
9
10
11
SEE SEPERATE PARTS LIST, SAME DRAWING NO.
LIST OF MATERIALS
APPLICATION
IMPINGER ASSY.
D
50726
7233-065
A
B
C
D
1
2
3
4
5
6
7
8

Figure 24. Assembly drawing, impinger train.

streams high in chlorides or fluorides. A Teflon bellows connector for eliminating any possibility of corrosion is now standard. The remaining components of the impinger assembly (shown in Figure 22) include a thermocouple to monitor temperature of the gas exiting the silica gel, a small pump to agitate the ice/water slurry surrounding the bottles, a carrying tray so the entire impinger assembly can be lifted out of its ice bath when required, and a coiled tube that acts as a heat exchange surface to cool the organic module. Figure 25 shows the assembled impinger train in its fiberglass case. The fiberglass case serves two purposes: it acts as a shipping case for the impinger assembly, and it holds the ice and water coolant during sampling operations.

4.5 VACUUM PUMPS

Two vacuum pumps connected in series are used with the SASS. The pumps are identical to the pumps used with the HVSS train. These carbon vane-type pumps (Gast Model 1022) are modified by Acurex with a special shaft seal to reduce the leak rate to better than Method 5 standards. Each pump has a 3/4-hp motor, a flowrate of 10 acfm at zero pressure drop, and weighs 59 lbs including all fittings. Each pump requires 10 amps/115 VAC. Figure 26 illustrates the pumps and associated fittings, gages, valves, and hoses. Pump features include:

- Smooth, pulse-free flow
- High vacuum capacity
- Self-lubricating carbon vanes
- Special shaft seal
- Coarse and fine flow control valves located on pump
- Carrying handle
- Operates in open air for good cooling

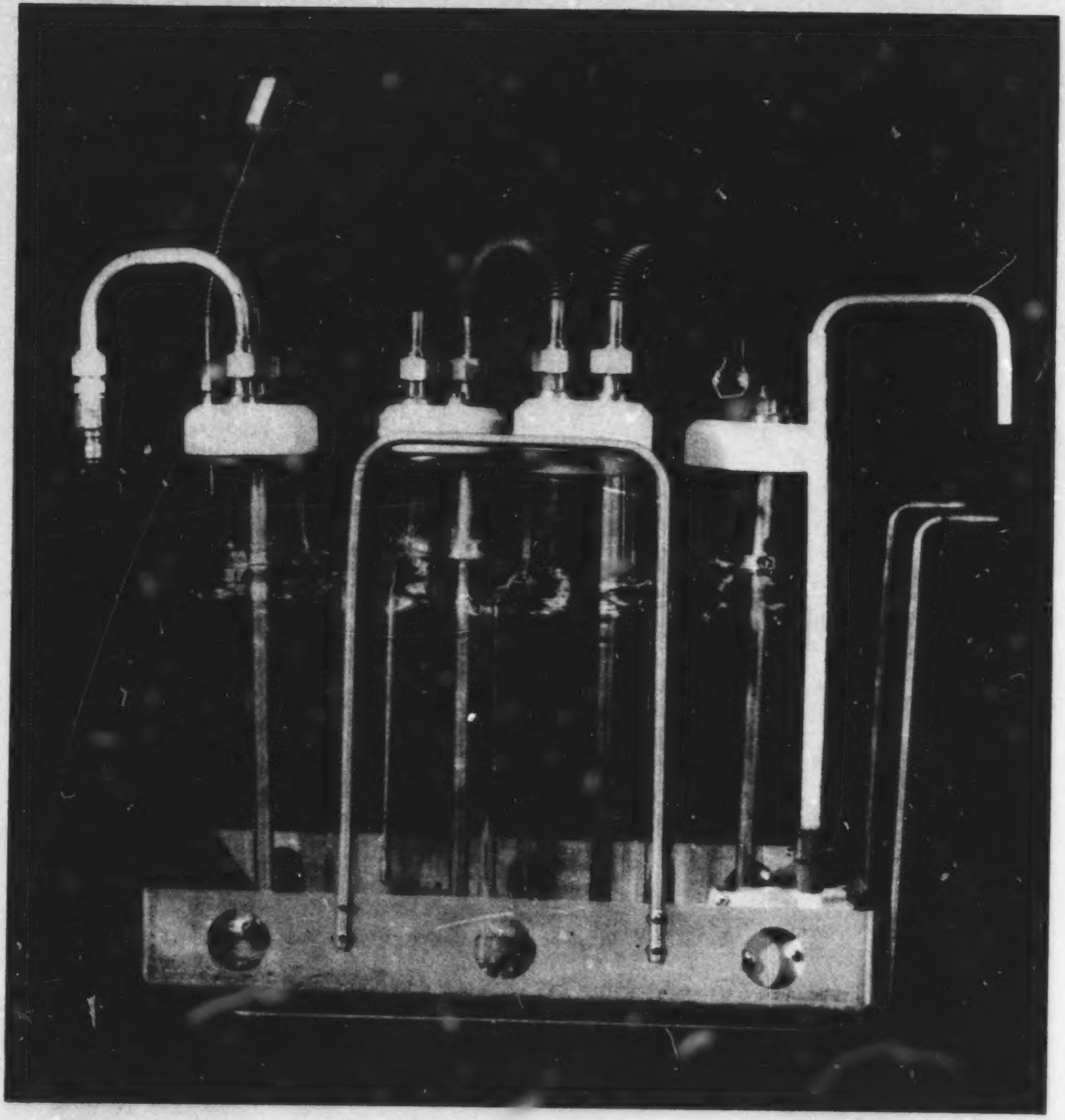


Figure 25. Impinger train.

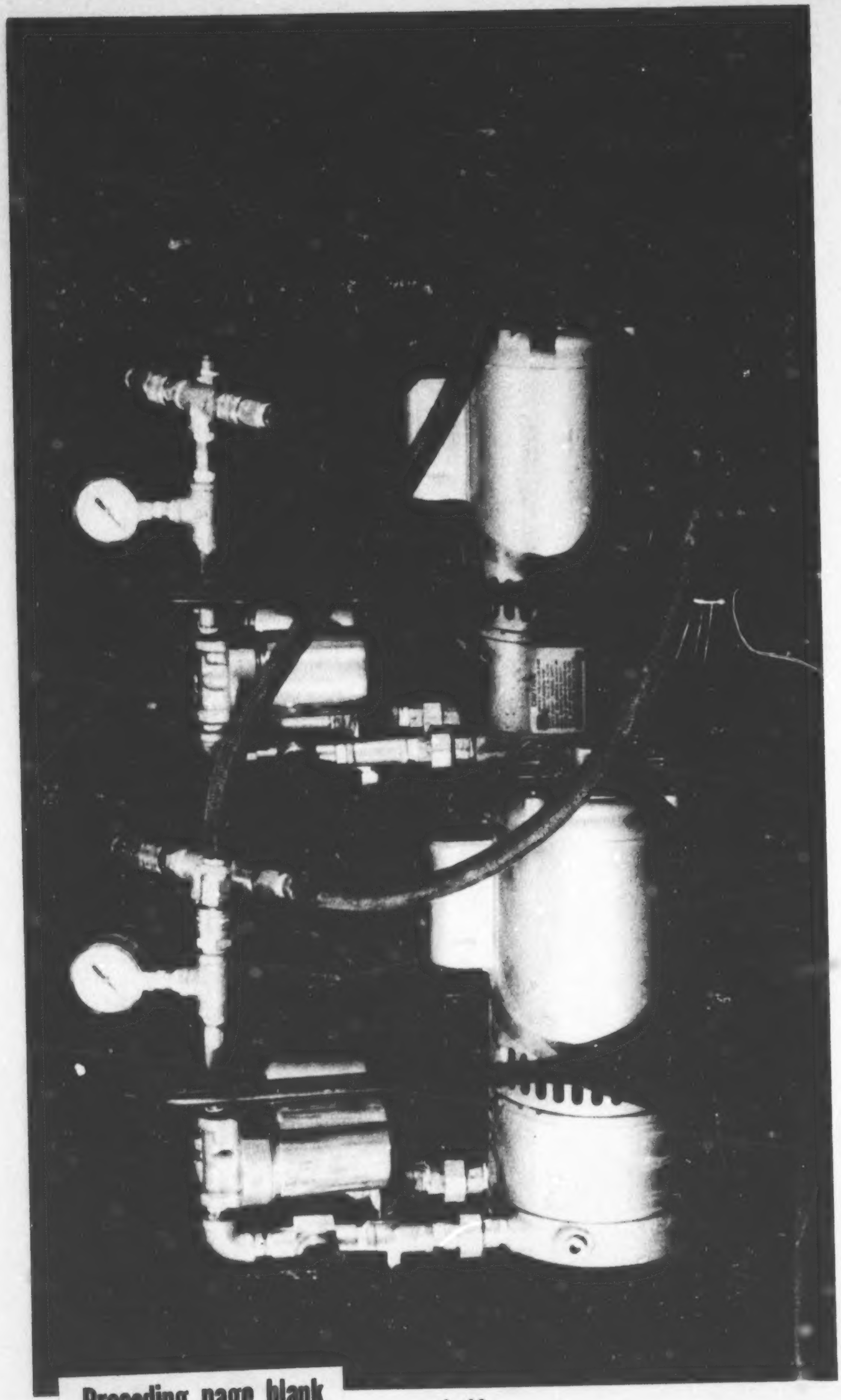


Figure 26. Vacuum pumps

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- Aluminum filter and muffler jars
- Vacuum gage to indicate filter condition
- Quick disconnect fittings

Figure 27 illustrates the construction of the Gast Model 1022 vacuum pump.

4.6 CONTROL UNIT

The control unit contains all of the instruments for measuring stack velocity, sampling flowrate and cumulative flow, and temperatures at various points in the sampling system (Figure 28). All of the controls for the sampling system are located in the control unit except the valves for controlling sample flowrate. The valves are mounted on the vacuum pump, which is placed adjacent to the control unit when using the sampling system. Thus all of the controls and measurement displays are centered about the control unit.

The SASS control unit is identical with the HVSS control unit, even through some HVSS control unit components such as the dry gas meter, the interchangeable orifice plates, and the timer are not necessary for Level 1 sampling. There are three reasons for not modifying the HVSS control unit. First, it was desired that the SASS and HVSS sampling trains should share as many interchangeable parts as feasible, since many users will own both trains (discussed in Appendix C). Second, even though the cost of a SASS control unit without unnecessary components would be lowered, the design costs for the new control unit would largely offset any savings. And third, in the future it may be desirable to use the SASS for some Level 2 procedures for which accurate gas flowrate measurement would be required.

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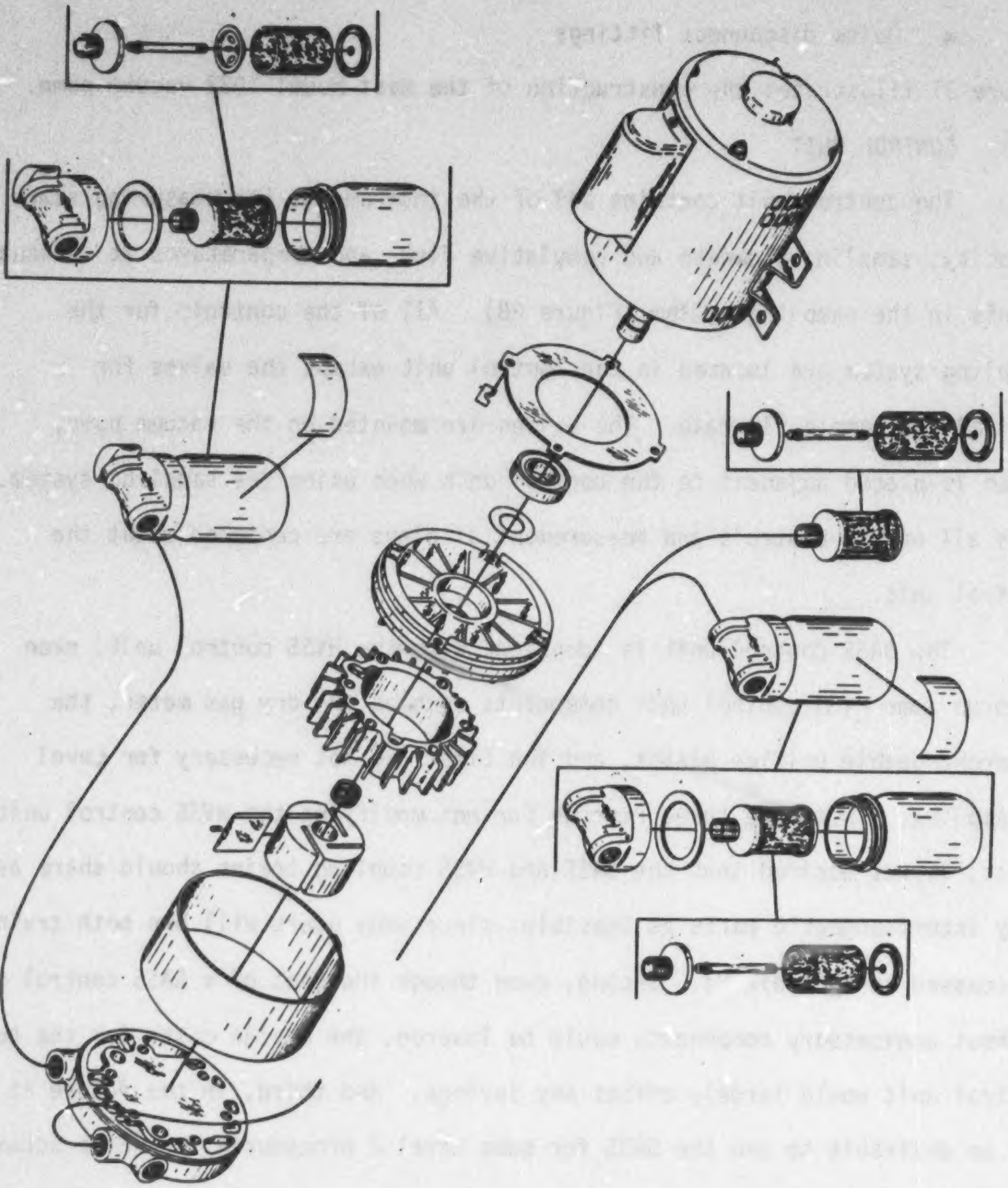

Figure 27. Construction of Gast 1022 vacuum pump.

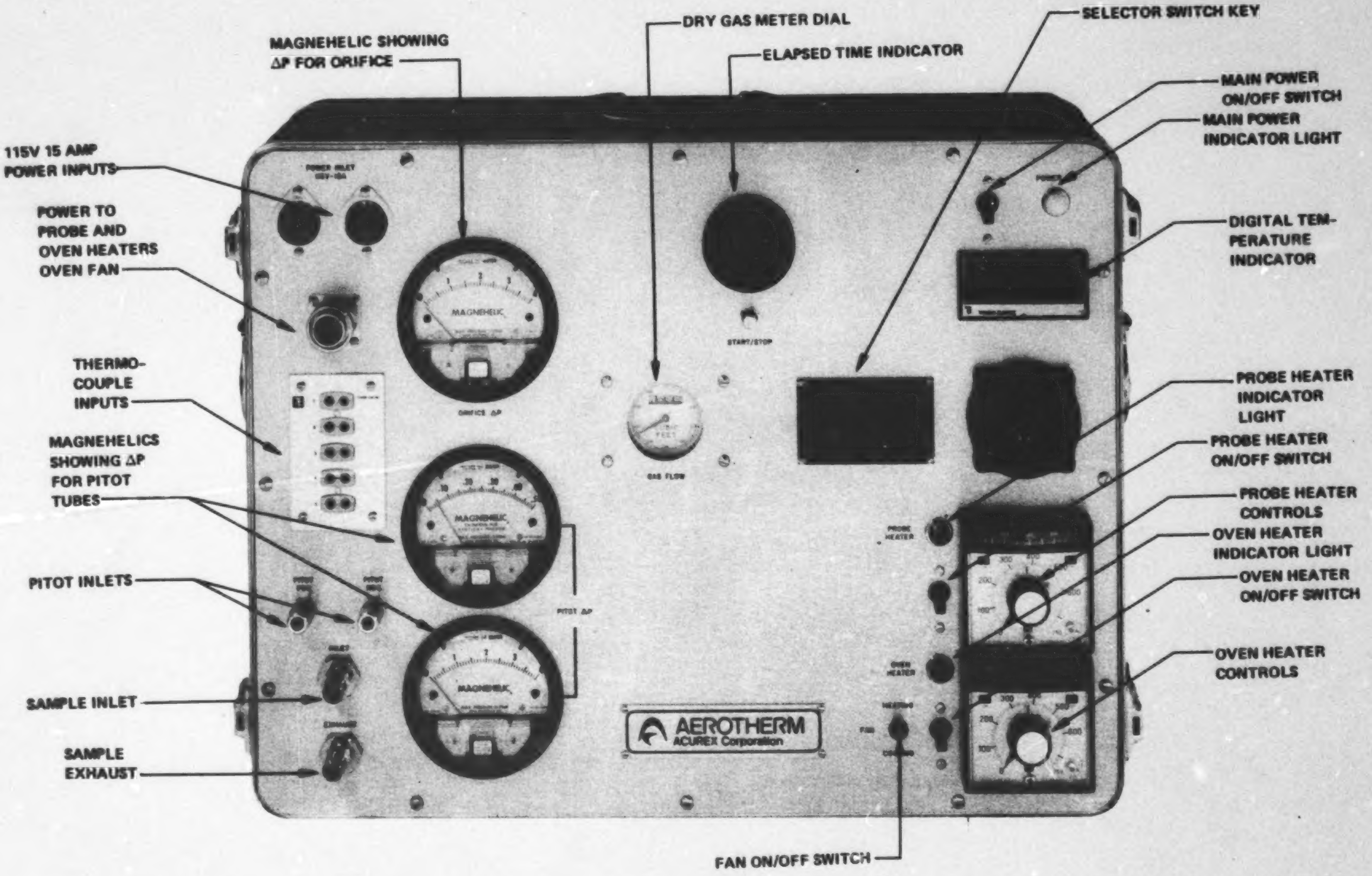
MAGNEHELIC SHOWING ΔP FOR ORIFICE
DRY GAS METER DIAL
ELAPSED TIME INDICATOR
SELECTOR SWITCH KEY
MAIN POWER ON/OFF SWITCH
MAIN POWER INDICATOR LIGHT
115V 15 AMP POWER INPUTS
POWER TO PROBE AND OVEN HEATERS OVEN FAN
DIGITAL TEMPERATURE INDICATOR
THERMOCOUPLE INPUTS
MAGNEHELICS SHOWING ΔP FOR PITOT TUBES
PROBE HEATER INDICATOR LIGHT
PROBE HEATER ON/OFF SWITCH
PROBE HEATER CONTROLS
OVEN HEATER INDICATOR LIGHT
OVEN HEATER ON/OFF SWITCH
OVEN HEATER CONTROLS
PITOT INLETS
SAMPLE INLET
SAMPLE EXHAUST
FAN ON/OFF SWITCH
MAGNEHELIC
ORIFICE ΔP
PITOT ΔP
GAS FLOW
START/STOP
PROBE HEATER
OVEN HEATER
AEROTHERM
ACUREX Corporation

Figure 28. Control unit.

The various switches, gages, and connections seen on the face of the control unit are described below:

Switches

There are five electrical switches with the following functions:

- Main power (with pilot light and 3-ampere, 115-VAC circuit breaker)
- Probe heater (with pilot light and 15-ampere, 115-VAC circuit breaker)
- Oven heater (with pilot light and 15-ampere, 115-VAC circuit breaker)
- Fan power
- Elapsed time indicator start/stop switch

Circuit breakers are used instead of fuses to avoid the problem of running short of fuses. The oven circulation fan is connected so that during heating, the fan is in operation regardless of the position of the fan control switch. When the oven heater is "off," the fan may be turned "on" with the oven door open to hasten cooling of the oven, cyclones, and filter.

Elapsed Time Indicator

An elapsed time indicator is used to determine when to move from one traverse point to the next, when performing Method 5 sampling. It is also useful for SASS sampling to monitor impinger solution change intervals, data logging intervals, and total sampling time. The indicator has a resolution of 1/10 of a minute. The indicator can be reset to zero, and started or stopped with a pushbutton located near the indicator.

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Oven and Probe Heater Temperature Controls

Power to the oven and probe heating elements is modulated with adjustable temperature controllers. These controllers use chromel-alumel thermocouples for temperature sensing. Each controller has the following features:

- Actual temperature continuously displayed
- Maximum set-point is limited to 500°F by a mechanical stop
- Power cycling is indicated by red and green lights

The oven and probe heater controls are located on the control unit because under some conditions the oven is inaccessible for adjustment. For example, while sampling large stacks, the oven may be located beyond the edge of the sampling platform. Feedback control of the temperature is used because the ambient conditions under which stack sampling is performed are highly variable. The concern for accurate temperature control is based on the fact that many of the effluents sampled have condensible components. These components, such as, water and sulfur oxides, must be maintained as vapor prior to filtering out the particulates. Also, the cyclones require constant temperature operation.

The actual switching of power to the heating elements in the probe and oven is done by heavy duty relays (lower right corner, Figure 29). This greatly increases the capacity for the system to use longer probes which require greater power.

Temperature Display

A digital temperature indicator is used together with an eight-point selector switch. The selector switch permits monitoring the temperature at each of the following locations:

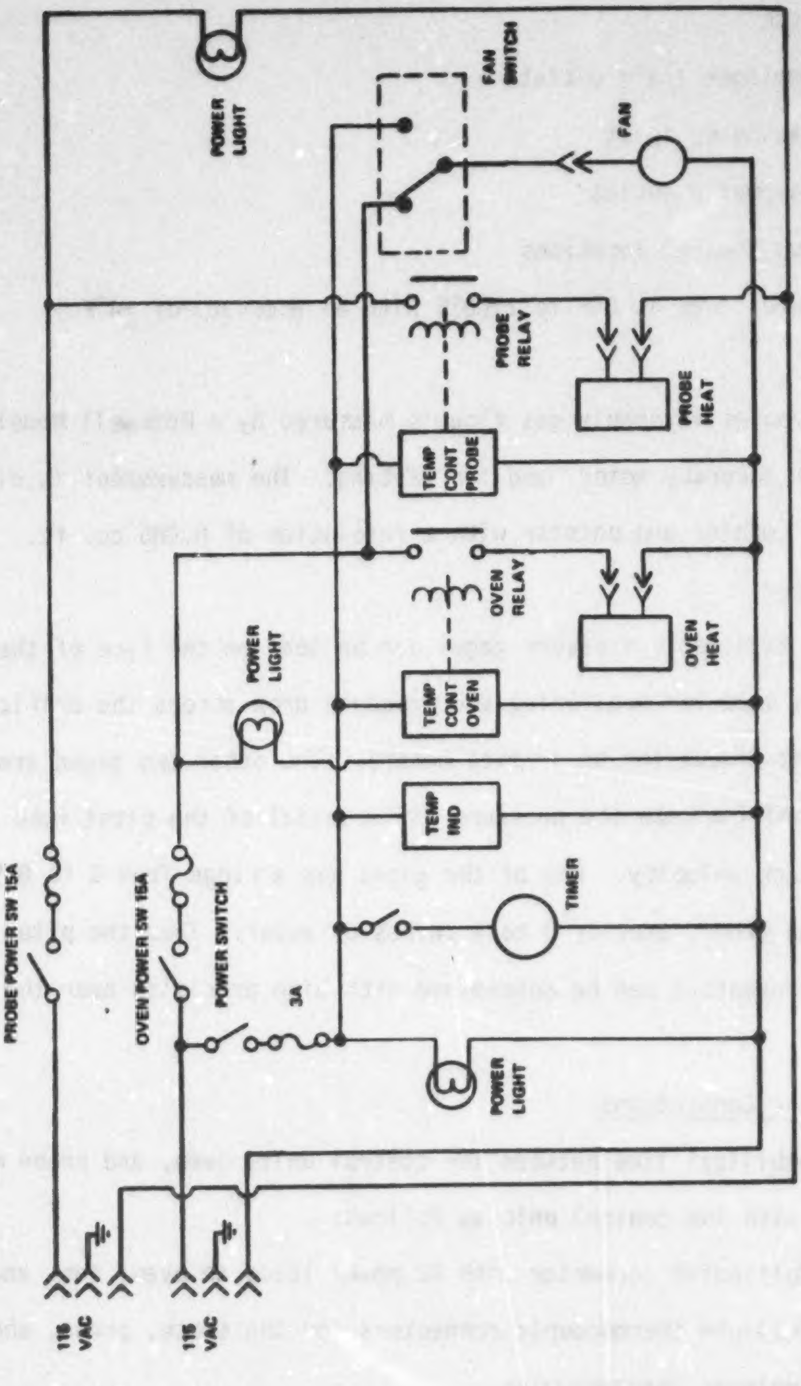

POWER LIGHT
FAN SWITCH
FAN
PROBE RELAY
PROBE HEAT
TEMP CONT PROBE
OVEN RELAY
OVEN HEAT
POWER LIGHT
TEMP CONT OVEN
TEMP IND
TIMER
PROBE POWER SW 15A
OVEN POWER SW 15A
POWER SWITCH
3A
POWER LIGHT
115 VAC
115 VAC

Figure 29. Control unit wiring schematic.

- Stack
- Probe
- Oven
- Impinger train outlet
- Gas meter inlet
- Gas meter outlet
- Two "spare" locations

The temperature range is 0°F to 1500°F with an accuracy of ±4°F.

Gas Flow

The cumulative sample gas flow is measured by a Rockwell Model 415 gas meter, a high accuracy meter used for testing. The measurement is displayed by a digital counter and pointer with a resolution of 0.005 cu. ft.

Pressure Gages

Three Magnehelic pressure gages can be seen on the face of the control unit. One is used for monitoring the pressure drop across the orifice meter (see following discussion on orifice meter). The other two gages are connected in parallel and indicate the pressure differential of the pitot tube used for measuring stack velocity. One of the gages has a range from 0 to 0.5 inches of water; the other, usually 0 to 4 inches of water. Thus the pitot tube pressure differential can be determined with high precision over the full range.

Umbilical Line Connections

The umbilical line between the control unit, oven, and probe makes the connections with the control unit as follows:

- Multipoint connector with AC power leads to oven, fan, and probe
- Dual-pin thermocouple connectors for the stack, probe, and impinger thermocouples.

The separate 25-foot sample hose connects to the vacuum pumps. The exhaust hose of the pump is conected to the "inlet" fitting located on the control unit. The sample gas then passes through the gas and orifice meters in the manner of the typical Method 5 sampling train.

A quick-disconnect fitting is provided at the sample "exhaust" outlet on the control unit. A length of tubing can be connected at this point for leading toxic sample gases away from the control unit area.

The control unit has a removable back cover to provide ease of access for repairs and to set the three-position orifice meter (right side, Figure 29). Three orifices are used for high accuracy measurements over the following flow ranges:

- 0.3 to 1.3 cfm
- 1.0 to 3.0 cfm
- 2.0 to 6.0 cfm

For Level 1 sampling, the largest orifice (highest flowrate) will always be used.

4.7 SYSTEM SPECIFICATIONS

Table 2 shows the size, weight, and electrical specifications for the SASS components. Four 20-amp circuits or three 30-amp circuits are recommended when using the SASS. Ice consumption for a 5-hour Level 1 test will vary somewhat with ambient temperature, but should not exceed 175 lb. Average ice use is 100-150 lb.

TABLE 2. SASS SYSTEM SPECIFICATIONS

Component	Size	Weight	Electrical	
			Voltage	Maximum Amperage
Probe	5 ft x 3 in.	15 lb.	115	5.5
Oven	22 x 15 x 22 in.	30	115	10
Cyclones/Filter	21 x 16 x 15 in.	18	--	--
Organic Module	20 x 25 x 9 in.	40	115	6
Impinger Assy	19 x 20 x 10 in.	35	115	1
Pumps (each)	16 x 18 x 9 in.	60	115	10
Control Module	26 x 20 x 15 in.	70	115	1

SECTION 5

CYCLONE CALIBRATION

The characterization of the SASS cyclones has been underway almost continuously since the development of the SASS. Initial efforts were conducted by Southern Research Institute using a Vibrating Orifice Aerosol Generator. Later calibration tests were performed by Acurex using a different method involving dispersions of polydisperse aluminum spheres. At the time of writing, results have been obtained with both methods that are reasonably consistant and are believed to represent the actual performance of the cyclones.

The object of the various cyclone calibration tasks ultimately is to determine the cyclone efficiency curve; from the curve can be obtained a commonly used figure-of-merit for the cyclone called the D_{50} cut diameter. Figure 30 illustrates these concepts. The efficiency of particle collection is plotted against the particle diameter. For each particle diameter, therefore, the effectiveness of the cyclone is determined. For example, Figure 30 shows that for this particular (ficticious) device, if a large number of 2.5-μm diameter particles are introduced, 17.5 percent will be collected and 82.5 percent will pass through uncollected. The particle diameter at which half of the particles are collected is the D_{50} cut

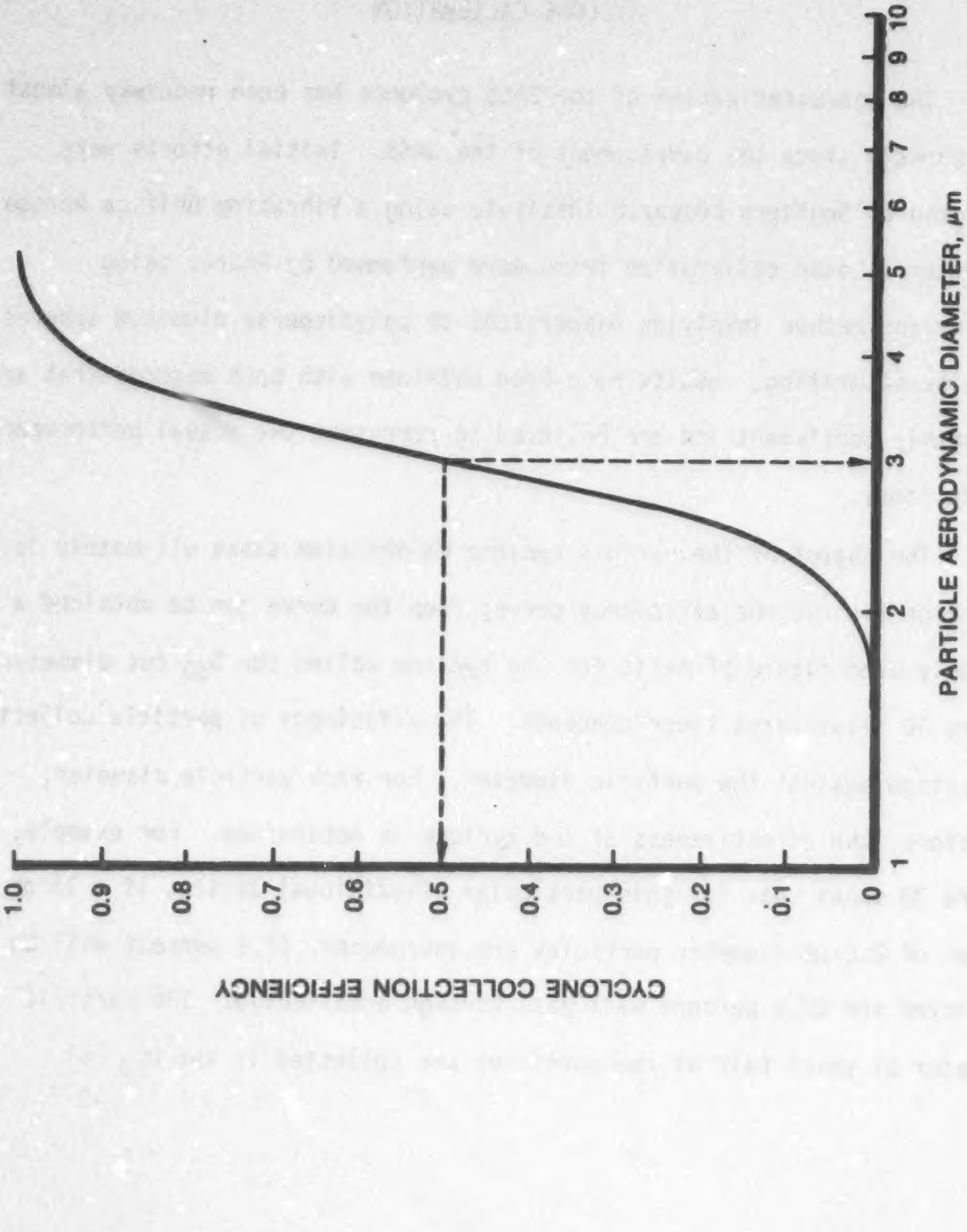


Figure 30. Typical cyclone fractional efficiency curve.

diameter; Figure 30 shows the D_{50} cut diameter of that device to be 3.0 μm. The D_{50} cut diameter, often abbreviated to "cut size," is commonly used as a rough indication of the collection cut-off of a cyclone.

Note that Figure 30 expresses particle diameters as aerodynamic particle diameters. It is important to distinguish aerodynamic diameters from physical diameters. The physical diameter is the dimension of the particle obtained by physical measurement, for example with a microscope and reticle. For nonsymmetrical particles, the physical diameter of a given particle may have several different values, depending on the measurement axis chosen. The aerodynamic diameter (sometimes called the Stokes diameter) is defined as the diameter of the equivalent spherical particle of unit specific gravity having the same terminal settling velocity as the particle in question. The advantages of using the aerodynamic diameter to characterize the particles used for cyclone calibration are twofold. First, each particle is uniquely characterized, independent of any choice of physical dimension. Second, and most important, since the basic cyclone separation mechanism depends on Stoke's law, measuring particle diameter in terms of Stoke's law behavior assures that calibration data will be valid over wide ranges of particle size, shape, and density.

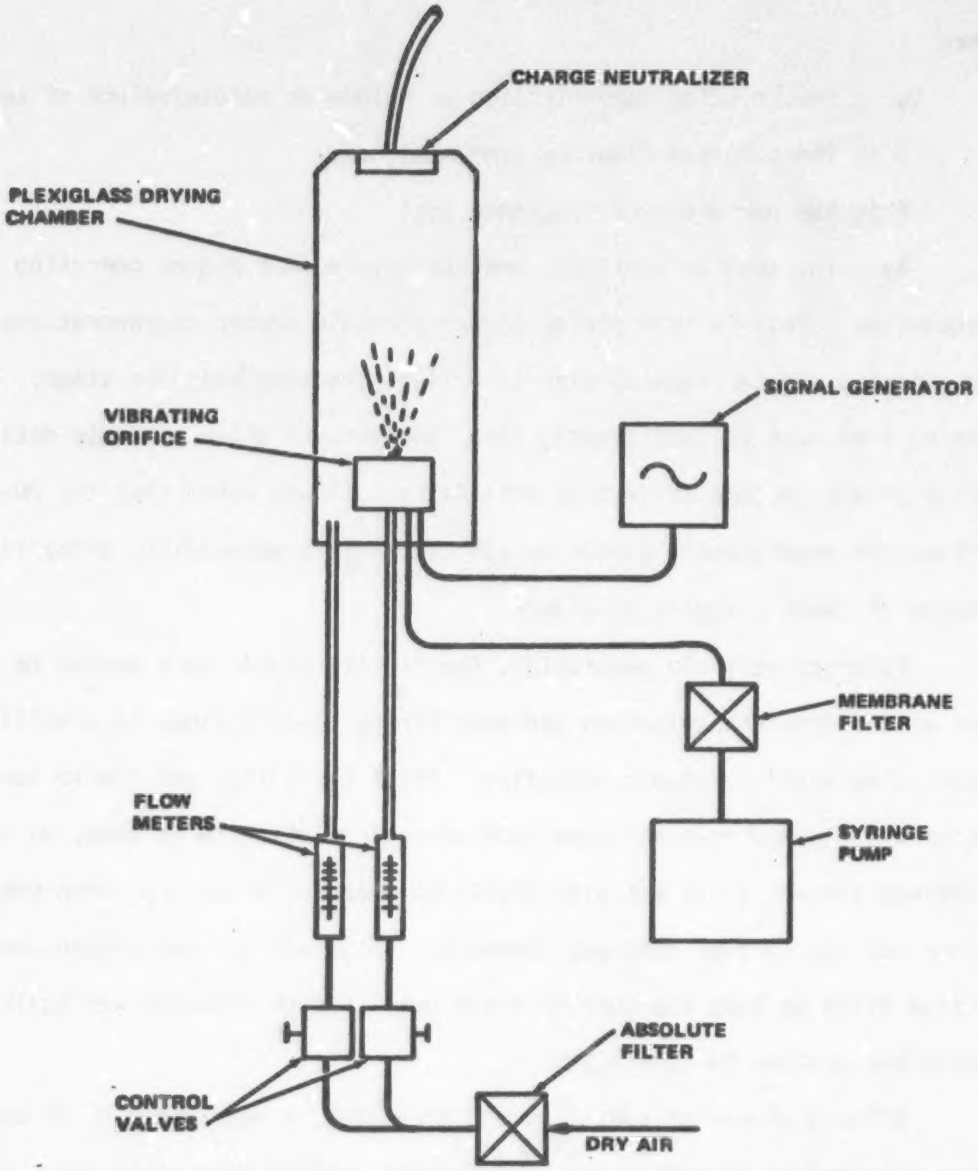
5.1 MONODISPERSE AEROSOL CYCLONE CALIBRATION TESTS

The Southern Research Institute (SoRI) calibration efforts using monodisperse aerosol occurred in two phases. Initial calibrations were made at room temperature, with the intent of calculating cyclone D_{50} cut diameters at 400°F by use of accepted design equations. Based on these initial calculated values, certain modifications were made to the cyclones to shift their cut points closer to the 1, 3, and 10 μm values desired. It was discovered subsequently that the design equation used to adjust the cyclone D_{50}'s to 400°F was inapplicable to small cyclones such as the SASS. The second phase of calibrations at SoRI involved actual calibrations at 400°F. These efforts resulted in calibration data (for the middle cyclone only) that are believed to be accurate.

5.1.1 Monodisperse Aerosol Cyclone Calibration Method

The same basic procedure has been used in all of the SoRI calibration work (Reference 9). The SASS train cyclones were calibrated using a Vibrating Orifice Aerosol Generator (VOAG). The VOAG generated monodisperse ammonium fluorescein particles and turquoise dye particles with diameters from 2 micrometers to 7 micrometers. The VOAG used in this study was designed and built at SoRI. However, similar devices have been reported by several authors previously, and a commercial unit is available from Thermo Systems, Inc.

Figure 31 is a schematic diagram showing the operating principle of the VOAG. A solution of known concentration (in this case, a solution of fluorescein ($C_{20}H_{12}O_5$) in 0.1N NH_4OH or a solution of turquoise dye in water) is forced through a small orifice (5-, 10-, 15-, or 20-μm diameter). The orifice plate is attached to a piezoelectric ceramic which, under electrical stimulation, will vibrate at a known frequency. This vibration imposes periodic perturbations on the liquid jet causing it to break into uniformly sized droplets. Knowing the liquid flowrate and the perturbation frequency, the droplet size can be readily calculated. The solvent is evaporated from the droplets leaving the nonvolatile solute as a spherical residue. The final dry particle size can be calculated from the droplet size through the known concentration of the liquid solution.



CHARGE NEUTRALIZER
PLEXIGLASS DRYING CHAMBER
SIGNAL GENERATOR
VIBRATING ORIFICE
MEMBRANE FILTER
FLOW METERS
SYRINGE PUMP
ABSOLUTE FILTER
CONTROL VALVES
DRY AIR

Figure 31. Schematic representation of the vibrating orifice aerosol generator.

To calculate the dry particle size, the expression

$$d_p = (QC_V/10\pi F)^{1/3}$$

where

C_V is the solution concentration or volume of solute/volume of solution

Q is the solution flowrate (cm^3/min), and

F is the perturbation frequency (Hz)

By using smaller orifices, one can obtain much higher operating frequencies. This in turn yields higher particle number concentrations and allows a shorter running time to collect the same mass per stage. The running time must be sufficiently long, however, to allow accurate determination of the cyclone collection efficiency. It was found that the 20-µm orifice was consistently easier to use in particle generation, primarily because of fewer clogging problems.

Prior to particle generation, the orifice plates were washed in detergent with ultrasonic agitation and then rinsed several times in distilled water, also with ultrasonic agitation. After the filter and liquid handling system was flushed several times with aerosol solution to be used, an orifice plate was placed, still wet with distilled water or blown dry, into the crystal holder and the syringe pump was turned on. A jet of air was played over the orifice plate to keep the surface clean until enough pressure was built up behind the orifice to form a jet.

After a stream of particles was generated, a determination of monodispersity had to be made. Two methods were used to accomplish this. By using a small, well-defined air jet to deflect the stream of particles, it was possible to tell when the aerosol was mono or polydisperse. Depending on particle size, the stream was deflected by the air at different angles. If the aerosol was polydisperse, several streams could be seen at one time. By varying the crystal oscillation frequency, the system could be fine-tuned to give only a single deflected particle stream, indicating monodispersity. The particle stream was then dispersed and diluted in a plexiglass cylinder 6 inches in diameter and 18 inches high through which dry, clean air flowed at 0.83 cfm. Polonium 210 alpha particle sources were placed around the dispersed particle stream at the orifice and at the outlet of the plexiglass cylinder around the exiting aerosol stream to act as charge neutralizers to reduce agglomeration and loss of particles due to electrostatic forces. A second check of monodispersity and particle size was optical microscope examination of a filter on which particles were collected as they exited from the outlet of the plexiglass cylinder. In general, it was found that about 4 percent to 8 percent by mass of the particles were twice the volume (1.26 x diameter) of the primary particles. Microscopic photography was used as a validation of monodispersity and particle size.

When it had been determined that particles of the correct size were being generated, a pump was started which was preset to give the correct actual flowrate through the cyclone. The aerosol stream flowed at the rate of 0.83 cfm from the outlet of the plexiglass mixing column, and to this heated room air was added at a rate and temperature to give the final indicated flowrate and temperature. The heated aerosol stream then entered the cyclone, which was kept in an oven and at or near the aerosol stream temperature. A glass fiber filter caught all the particulate that passed the cyclone.

On several occasions, the aerosol tended to drift from monodispersity. In order to avoid sampling a polydisperse aerosol, periodic filter samples of the heated aerosol stream were taken and checked by optical microscopy. This also provided a good check on the sphericity of the aerosol because the final particles instead of the primary liquid droplets were investigated.

Throughout the testing, close watch was kept on the temperature and flowrate of the aerosol stream. Any discrepancies were quickly corrected, and readings of all temperatures were recorded periodically to insure repeatability of the tests and test results.

After each test, the cyclone and filter substrate were washed to dissolve and rinse off all the aerosol particles. The wash solutions used were 0.1N NH_4OH for ammonium fluorescein and distilled water for turquoise dye.

A Bausch and Lomb Spectronic 88 Spectrophotometer, calibrated with solutions of known concentration of the aerosol solute (turquoise dye or ammonium fluorescein), was used to measure the absorbance of both the wash from the cyclone and the filter from which the concentration was determined. From knowledge of the amount of wash solution, the dilution factor, if any, and the absolute concentration, the mass of particles in the cyclone and on the filter was calculated. With these two masses known, the collection efficiency of the cyclone for that particular particle size was calculated.

5.1.2 Initial Monodisperse Aerosol Cyclone Calibrations

As previously described, the initial cyclone calibration tests on the SASS cyclone were conducted at ambient temperature to calculate performance at the 400°F SASS operating temperature. The Lapple equation (Reference 10) predicts the variation in D_{50} cut diameter with changes in other variables:

$$D_{50} = (9\mu\ B_c/2\pi N_c V_c \rho)^{1/2}$$

where

D_{50} = cyclone D_{50} cut diameter

μ = gas viscosity

ρ = density of particles

N_c = number of turns made by the gas stream in the cyclone body and core

B_c = width of the cyclone inlet

V_c = inlet air velocity

Table 3 shows the results of the initial SASS cyclone calibrations. The D_{50} values are calculated at 4.0 scfm (6.5 acfm) flowrate, 400°F temperature, and 1.0 specific gravity, although the actual measurements were made at 4.0 acfm, 75°F, and 1.35 g/cm^3 assuming the applicability of the Lapple equation. In fact, during later attempts to calibrate the cyclones at 400°F, it was found that the equation does not accurately predict parametric variation in small cyclones such as the SASS. Accordingly, it was concluded that the calibration values shown in Table 3 are incorrect, and that calibrations should be performed at the operating conditions of the SASS train (4.0 scfm and 400°F). This was done during the final calibration tests at SoRI.

5.1.3 Final Monodisperse Aerosol Cyclone Calibrations

Having decided to perform the SASS cyclone calibrations at 400°F, the major problem to be overcome was the thermal instability of the ammonium fluorescein dye used for previous room-temperature work. The first method attempted was to calibrate the cyclones at 70°F, 200°F, and 350°F and then to extrapolate the results to 400°F. This method proved to be unsatisfactory when it was found that -- contrary to expectations -- ammonium fluorescein particles smaller than 4 µm in diameter were unstable at 350°F. Attempts to alleviate this problem were largely unsuccessful. After some futher work, it was determined that ammonium fluorescein was not suitable for calibrations at elevated temperature. Attention was turned to finding a different dye material.

TABLE 3. SASS CYCLONE CALIBRATION INITIAL TESTS

Cyclone	Calculated D_{50} Values at 400°F, 4 scfm, 1.0 g/cm^3
Large	10.2
Middle	3.2
Small	0.80

Several strict requirements must be met by a satisfactory dye candidate. Most or all of the following characteristics must exist:

- Nontoxic
- Stable at temperatures up to 500°F or above
- Soluble in water or other nontoxic, nonresidue forming solvent
- Amporphous -- dries to form solid, homogeneous spheres when disperesed in solution from a VOAG
- Known or easily measured density
- Has a definite, distinct absorption spectrum peak for absorption spectroscopy measurement between 400 NM and 900 NM

Of several samples from three chemical companies, du Pont's "Pontamine" Fast Turquoise 8 GLP dye was the first found to satisfactorily meet the requirements listed above. A spectral analysis performed on a dilute water solution of this dye indicated a distinct absorption peak at 622 namometers. Measurements with a Helium-Air pycnometer gave a density of 2.04 gm/cm^3. The sample seemed pure and its stability at 400°F was excellent. The expansion problems encountered with small diameter ammonium fluorescein particles were absent. Aerosol particles made from a solution of the dye in distilled water were very nearly, if not perfectly, round.

When the high temperature calibrations technique was fully developed, primary interest was in the performance of the middle cyclone. Accordingly, only the middle cyclone was calibrated. As the first calibration tests indicated that the D_{50} cut diameter was somewhat larger than the 3.0 μm desired value, the middle cyclone was also calibrated with the vortex buster removed. The vortex buster is a sheet metal cross that is normally placed in the dust collection cup at the bottom of the cyclone. It breaks up the normal swirl pattern in the cyclone, thus reducing collection efficiency and increasing D_{50} cut diameter. The swirl buster had been added earlier, based on (erroneous) estimates that the D_{50} was too low.

The results of the high-temperature calibration of the middle cyclone are shown in Figure 32. Note that the physical particle diameter is used. The D_{50} physical cut diamters are 3.4 and 2.5 μm with and without the swirl buster. The D_{50} aerodynamic cut diameters are 4.9 and 3.5 μm respectively. These are obtained by using the Lapple equation to correct to unit particle density.

Table 4 summarizes all of the monodisperse aerosol cyclone calibration tests of the middle cyclone. The "correct" values of the D_{50} cut diameter are the Turquoise Dye aerodynamic values, that is, 3.5 μm without the vortex buster, and 4.9 μm with the vortex buster.

5.2 POLYDISPERSE POWDER CYCLONE CALIBRATION TESTS

The Acurex SASS cyclone calibration test series was conducted by an entirely different method than was used by SoRI. The Acurex method involves the dispersion of polydisperse particles, at concentrations representative of actual field conditions. It was desirable to do a second series of calibration tests for several reasons:

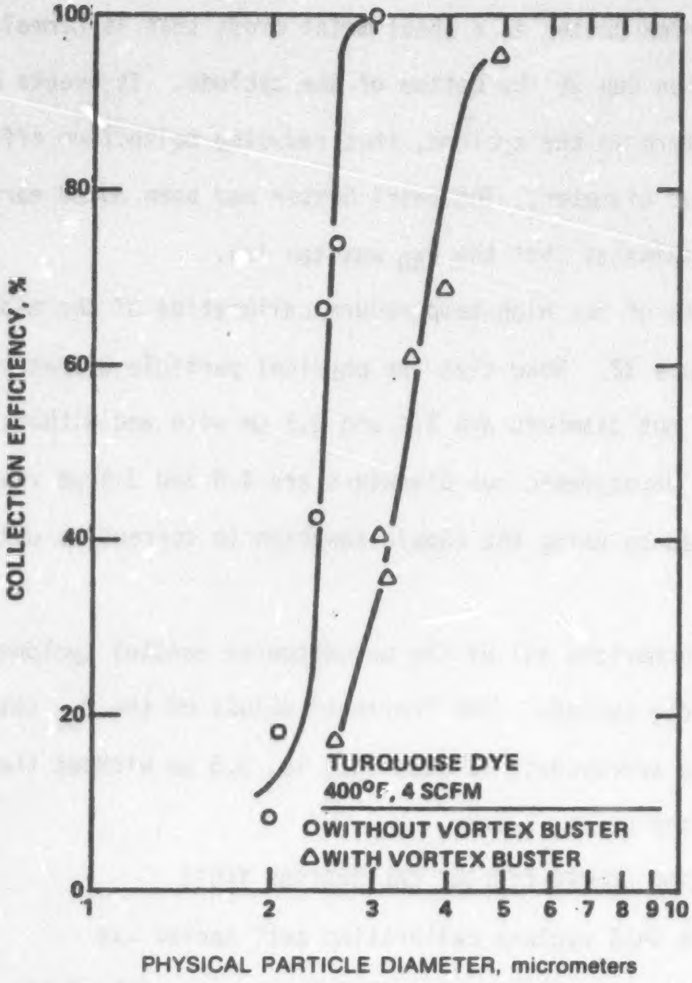


Figure 32. Collection efficiency at 400°F, 4 SCFM — SASS middle cyclone. Turquoise dye particle density = 2.04 gm/cm^3.

TABLE 4. SUMMARY OF MONODISPERSE AEROSOL CALIBRATIONS OF MIDDLE CYCLONE

Material	Vortex Buster	Temperature	Flow Rate ft.^{3}/min Actual/Standard	D_{50} Physical Micrometers	D_{50} Aerodynamic Micrometers
Ammonium Fluorescein	IN	Ambient	5.37/—	2.8	3.3
Ammonium Fluorescein	IN	200°F	5.41/—	3.5	4.0
Ammonium Fluorescein	IN	350°F	5.46/—	4.2	4.9
Turquoise Dye	IN	Ambient	5.42/—	2.2	3.1
Turquoise Dye	OUT	400°F	6.50/4.00	2.5	3.5
Turquoise Dye	IN	400°F	6.50/4.00	3.4	4.9

- A separate series of calibrations using a different method would -- if the results agreed -- greatly increase confidence in the correctness of the calibrations
- The extremely low particle mass concentrations with the SoRI calibration method required confirmation at more realistic loadings
- The physical state of the SoRI dye particles was unknown. There was a feeling that any stickiness caused by hydroscopic absorption might bias the results
- At the time the A/A tests began, problems with the SoRI method at elevated temperature made ultimate success with that method uncertain

The Acurex calibration program was not without its share of problems and false starts. Several different test dusts and data reduction methods were tried before successful calibration data were obtained. Throughout the program, however, the apparatus and basic method of conducting the calibrations was unchanged.

5.2.1 Polydisperse Powder Cyclone Calibration Method

Figure 33 shows the test apparatus in schematic form. Metered amounts of air and test dust are combined in a powder feeder. The powder feeder is so designed that the dust particles are deagglomerated and suspended in the air. The dust cloud then enters a heater, where its temperature is raised to the desired level. The hot dust cloud then enters the cyclone being evaluated. Each particle is either captured by the cyclone (ending up in the cyclone cup) or exits the cyclone and is captured on an absolute backup filter. Clean air is exhausted from the filter holder to the room.

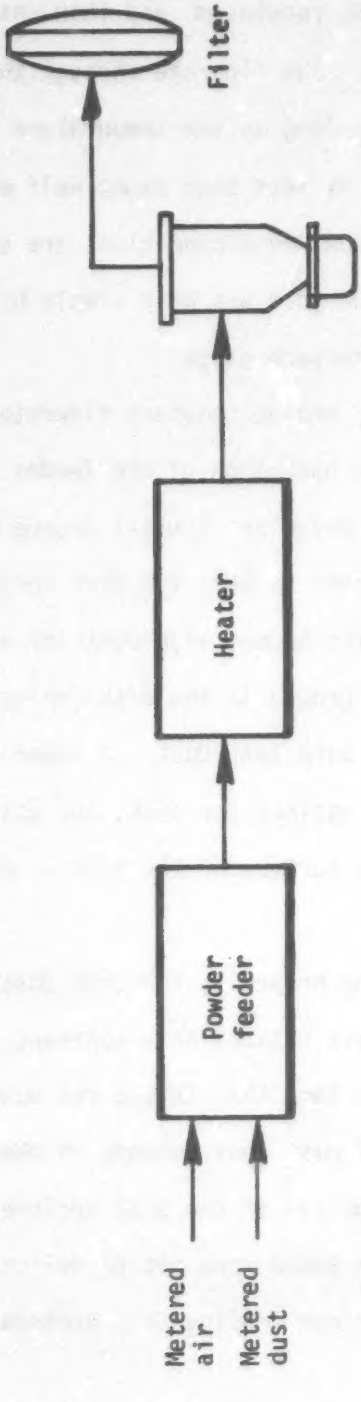

Metered air
Metered dust
Powder feeder
Heater
Cyclone
Filter

Figure 33. Polydisperse powder cyclone calibration apparatus schematic.

Figure 34 shows the apparatus in more detail, while Figure 35 shows a cutaway view of the dust feeder, the heart of the apparatus. As shown in Figure 34, compressed air is filtered, regulated, and then passed through a square-edged critical flow orifice. The flowrate through this type of orifice depends only on upstream pressure, so long as the temperature remains constant and the downstream absolute pressure is less than about half of the upstream pressure. In the calibration apparatus these conditions are easily met, so a constant volumetric flowrate of 4.00 scfm was held simply by maintaining a constant reading on the upstream pressure gauge.

The carrier air -- clean, dry, and at constant flowrate -- now enters the dust feeder. Figure 35 shows the operation of the feeder. The dust metering element is the feeder disk, which has a small groove milled coaxially on one face. The feeder motor rotates the disk continually. Test dust is stored in the dust hopper. The hopper also contains a rotating stirring shaft that assures that the groove in the disk (which passes directly under the hopper) is filled with test dust. A wiper arrangement on the outside of the dust hopper rides against the disk, and assures that the hopper dust is contained and that the surface of the disk -- except for the groove -- is free of dust.

If the dust feeder is operating properly, the test dust will be firmly packed into the groove. Since the disk rotates at a constant angular velocity, the amount of dust per unit time that leaves the dust hopper will be constant. The rate of delivery of dust thus depends on the size of the groove and its speed of rotation. For all of the SASS cyclone calibration tests, the groove size and rotational speed were set to deliver 0.26 grams/minute, which corresponds to a dust cloud loading of 1 grain/standard cubic foot.

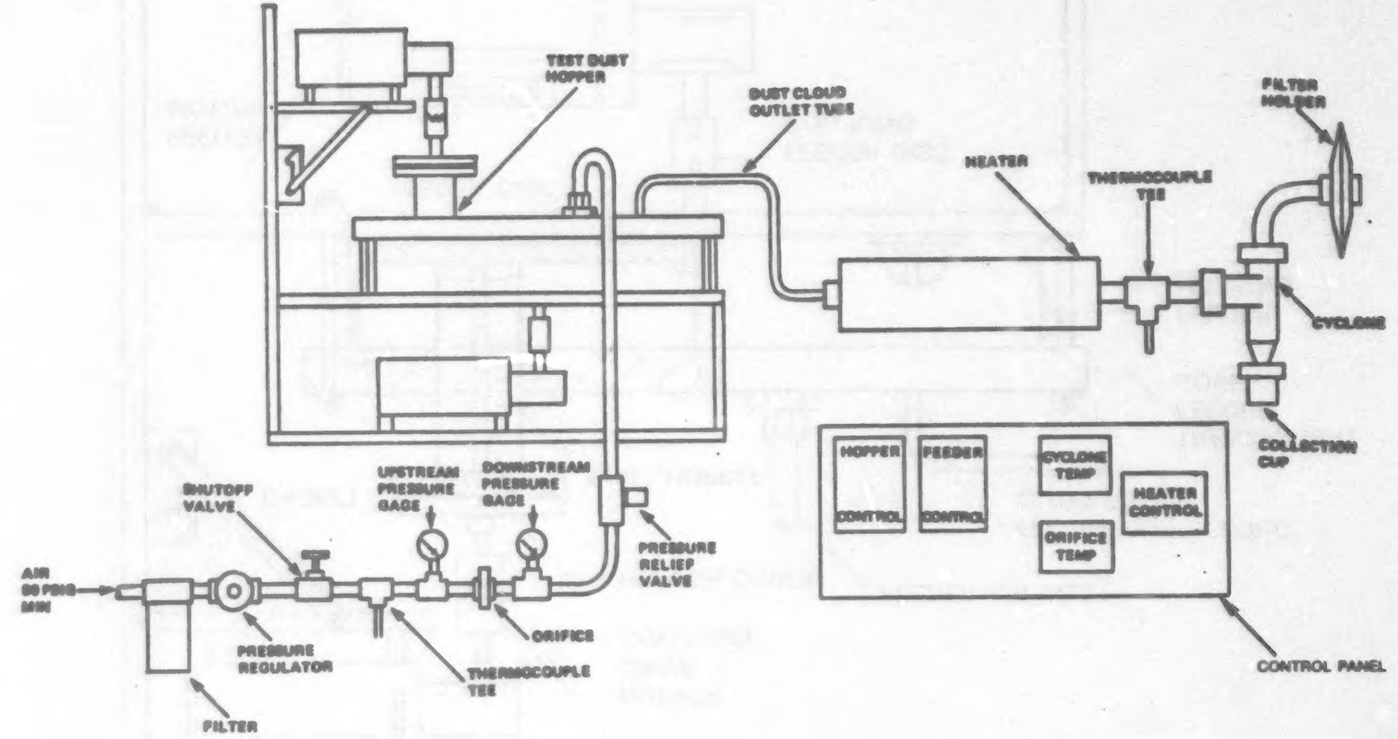

TEST DUST HOPPER
DUST CLOUD OUTLET TUBE
HEATER
THERMOCOUPLE TEE
FILTER HOLDER
CYCLONE
COLLECTION CUP
HOPPER CONTROL
FEEDER CONTROL
CYCLONE TEMP
ORIFICE TEMP
HEATER CONTROL
CONTROL PANEL
AIR
PSIG
MIN
SHUTOFF VALVE
UPSTREAM PRESSURE GAGE
DOWNSTREAM PRESSURE GAGE
PRESSURE RELIEF VALVE
PRESSURE REGULATOR
ORIFICE
THERMOCOUPLE TEE
FILTER

Figure 34. Detail of polydisperse powder cyclone calibration apparatus.

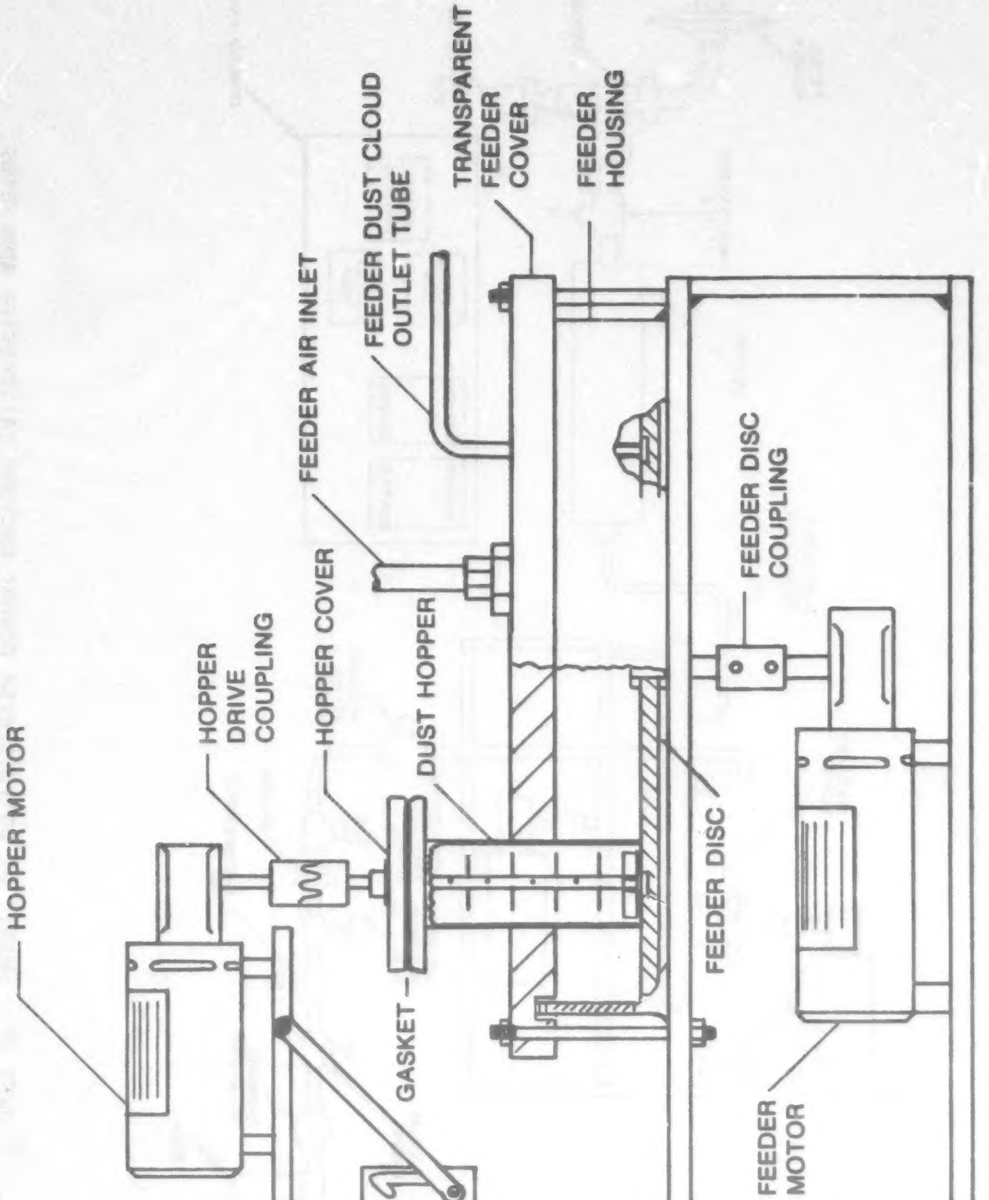

HOPPER MOTOR
HOPPER DRIVE COUPLING
HOPPER COVER
DUST HOPPER
FEEDER AIR INLET
FEEDER DUST CLOUD OUTLET TUBE
TRANSPARENT FEEDER COVER
FEEDER HOUSING
GASKET
FEEDER DISC
FEEDER DISC COUPLING
FEEDER MOTOR

Figure 35. Dust feeder.

Approximately 180° away from the dust hopper, and centered over the groove, is the feeder outlet tube (see Figure 35). Since the feeder is sealed, all of the air that enters through the air inlet tube must exit through the outlet. The end of the outlet tube is positioned just above the groove in the disk. The outlet tube is sized so the air velocity at the entrance is about 800 ft/sec. This high velocity air cleans all of the dust out of the groove and conveys it out of the dust feeder. The cleaned groove then rotates back to the dust hopper, where it is refilled.

In practice, the operation of the dust feeder is quite simple. Operator attention is required only periodically to see that the groove is being properly filled and to refill the dust hopper when needed. The high-velocity air at the feeder outlet tube does have a tendency to clean out the groove about a 1/4-inch ahead of the tube and some slugging (breaking away of the dust in the groove in chunks) is evident. Thus there are undoubtedly momentarily higher dust loadings than the 1 gr/scf average value.

The dust cloud velocity in the outlet tube is deliberately held at near sonic conditions in order to assure maximum dispersion of the dust particles. At the point the outlet tube enters the heater (see Figure 34), a step enlargement in the diameter of the tube reduces the gas velocity through the heater to about 400 ft/sec. The heater itself is simply a stainless steel tube wrapped with a heating tape. The wall temperature of the tube is maintained at about 600°F, allowing the dust cloud to reach 400°F by the time it exits the 20-inch long heater. Feedback temperature control of the exit dust cloud temperature is maintained by a thermocouple and temperature controller.

The cyclone being calibrated is attached to the outlet of the heater, and is wrapped with thermal insulation during calibration tests so the 400°F exit temperature is maintained. A standard SASS filter holder supports a glass fiber absolute filter.

Conduct of a calibration test is straightforward. The dust hopper is loaded with the desired test dust and a filter paper is preweighed and installed in the filter holder. The air and the heater are turned on. After temperatures have equilibrated, disk rotation is begun, starting the flow of test dust. The test continues for long enough (1 to 5 hours) to collect sufficient dust in the cyclone and on the filter for subsequent analysis. The disk rotation is then stopped, the heater is turned off, and after the system has cooled (about 30 minutes) the air is turned off and the samples are removed. Dust found inside the cyclones is brushed down into the collection cup. Dust found inside the cyclone outlet tube is added to the filter catch.

5.2.2 Initial Calibration Tests

In the first series of experiments undertaken, a highly classified silica dust material was used. The dust (AC Fine test dust) was classified by the Donaldson Company into nine size fractions. This particular material was chosen because of its availability, its wide use as a test dust in the HVAC industry, and the familiarity of Donaldson Company with the behavior of the material in their classifiers.

The approximate performance of each of the SASS cyclones was believed known from previous SoRI tests. Accordingly, three to six of the classified dusts were chosen for calibrating each cyclone, depending on the mean particle size of the dust and the anticipated cyclone cut size. The size distribution of the test dust and the dust collected in the cyclone cup was measured using the X-ray sedograph at EPA/RTP.

From the size distribution data, it should have been possible to construct a cyclone efficiency versus particle size curve for the particle size range of the test dust. When this was attempted, it became apparent that the experimental results were inconsistent, and in some cases, contradictory. For several experiments, for example, the mass median size of the cyclone cup catch was smaller than the feed material; the filter catch mass median diameter was even smaller. This result is clearly impossible unless the size distribution measurement method is faulty or unless the test dust is changing its characteristics during the test.

There is some evidence that the latter explanation is the cause of the unexpected test results. Figures 36, 37, and 38 are scanning electron micrographs of the feed, cyclone cup, and filter fractions, respectively, from a calibration run with the small cyclone. The magnification is 3000X. It is qualitatively apparent that the cyclone cup fraction is smaller than the feed fraction, as indicated by the X-ray Sedograph measurements. The most interesting point, however, is the appearance of the particles. The test dust particles (Figure 36) are generally smooth and show cleavage planes. The particles collected by the cyclone (Figure 37), however, are very rough and pitted, and seem to be rounded off. The filter fraction largely consists of very small particles that are not evident in the test dust. All of this seems to indicate that the test dust has been eroded and reduced in average size somewhere in the calibration apparatus. As velocities in the dust cloud outlet tube and heater are deliberately kept high (near sonic) to avoid reagglomeration of the dust, it is suspected that particle-particle contact in this region is causing the erosion. The hardness and frangibility of the test dust undoubtedly is also a major factor.

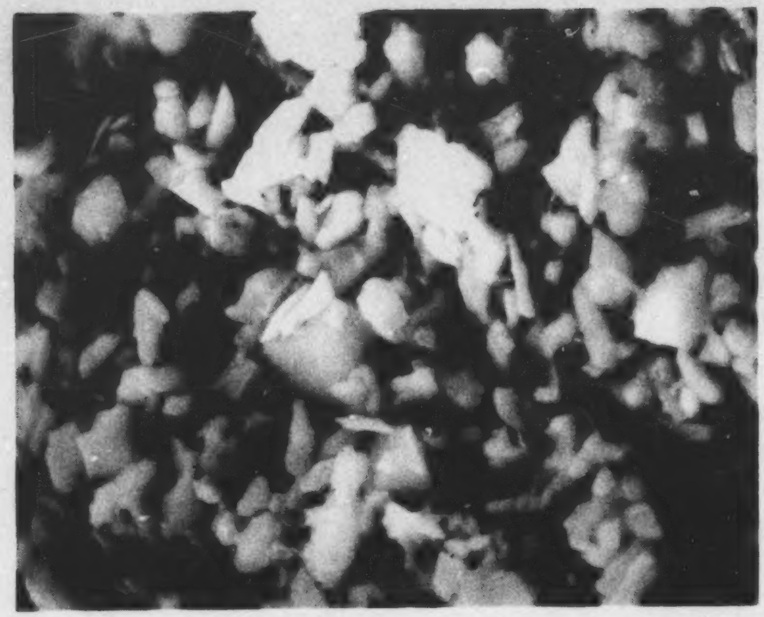


Figure 36. SiO_2 test dust.

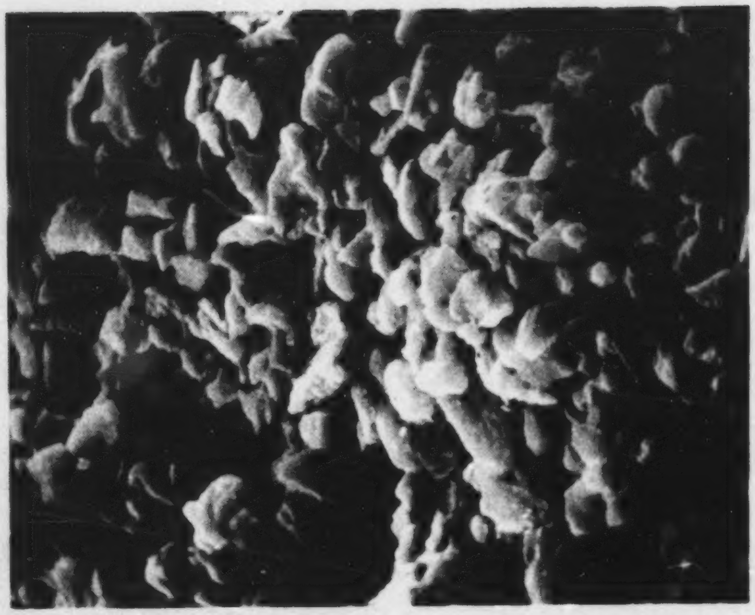


Figure 37. SiO_2 -- small dust cyclone cup catch.

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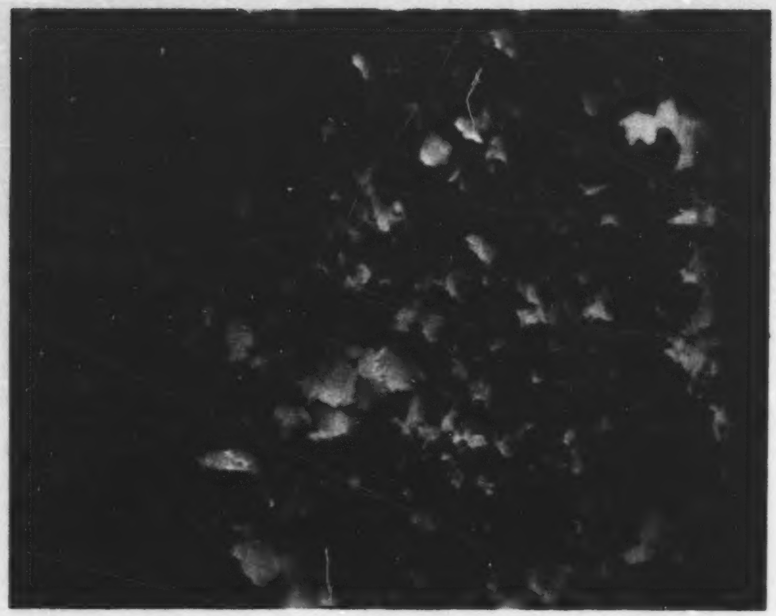

Figure 38. SiO_2 test dust -- small cyclone filter catch

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It was clear that to overcome the problem of test dust degradation, either the apparatus or the test dust would have to be changed. The easiest solution appeared to be to use a test dust not subject to erosion. After considering several alternatives, a spherical aluminum powder was chosen for the next series of tests.

5.2.3 Final SASS Cyclone Calibration Tests

The aluminum powder chosen is produced by several manufacturers by atomization from the melt. Individual particles are spheroidal, a large majority having the appearance of perfect spheres. Because the particles are malleable, erosion or other damage during the calibration operation was considered unlikely.

The data reduction method originally planned for use with the aluminum powder depended on measuring the size distribution of the material entering the cyclone, the amounts of material collected in cyclone dust cup and on the filter, and the size distribution of either the dust cup or the filter material. Knowing this information allowed calculation of the cyclone efficiency at each differential particle size. Coulter counter measurement was chosen for determining the distribution, since for the particle sizes of interest (1 μm to 20 μm) it was known to give reliable, reproducible, and relatively inexpensive results.

It quickly became apparent that the apparent size distribution of the test dust entering the cyclone was being changed during passage through the dust feeder and heater section of the test apparatus. Six tests were made in which the test apparatus was operated normally except no cyclone was attached -- all of the output of the apparatus was collected on an absolute filter. When the size distribution of the collected aluminum powder was measured, it varied noticeably from test to test. Aluminum powder as suppled by the

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manufacturer was very constant in size distribution, Figure 39 shows the results of these tests. As the aluminum test dust passed through the test apparatus, the size distribution gets larger -- agglomeration is occurring, small particles are somehow being removed, or both.

To overcome the problem of test-to-test variations in the test dust entering the cyclone being tested, a different data reduction strategy was used. The size distribution and quantity of dust collected in both the cyclone dust cup and on the filter is measured. From this information a simple material balance on each differential element of particle size allows reconstruction of the distribution of the test dust entering the cyclone, no matter how it may have been changed during passage through the dust feeder and heater. This method of analysis was used for the final, and successful, series of cyclone calibrations. Details of the data reduction method are given in Appendix A.

Two complete sets of SASS cyclones were calibrated. Each set consisted of three cyclones -- one small, one medium, and one large. The first set calibrated was a part of an EPA-owned SASS train. The large and medium cyclones were calibrated both with and without their swirl busters; thus a total of five complete cyclone calibrations were obtained. Figures 40 through 42 show scanning electron photomicrographs of the test dust and representative samples of dust collected by the cyclones. The spheroidal nature of the particles is easily seen.

Figure 43 shows the calibration results. Note that cyclone efficiency is plotted against physical particle diameter; converting to aerodynamic diameter requires correcting for the nonunit density of the aluminum particles. This conversion has been done in Table 5, which shows the D_{50} cut diameters for each of the five cyclone configurations expressed as

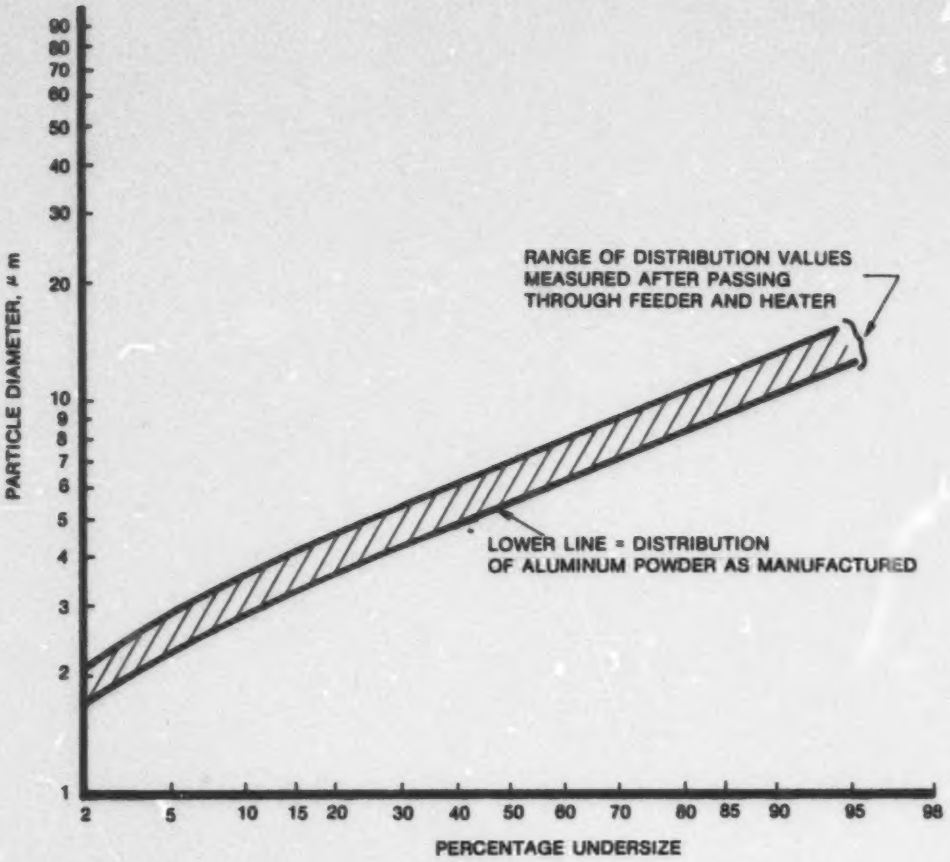

Figure 39. Results of tests of the constancy of the size distribution of aluminum powder passing through the test apparatus.

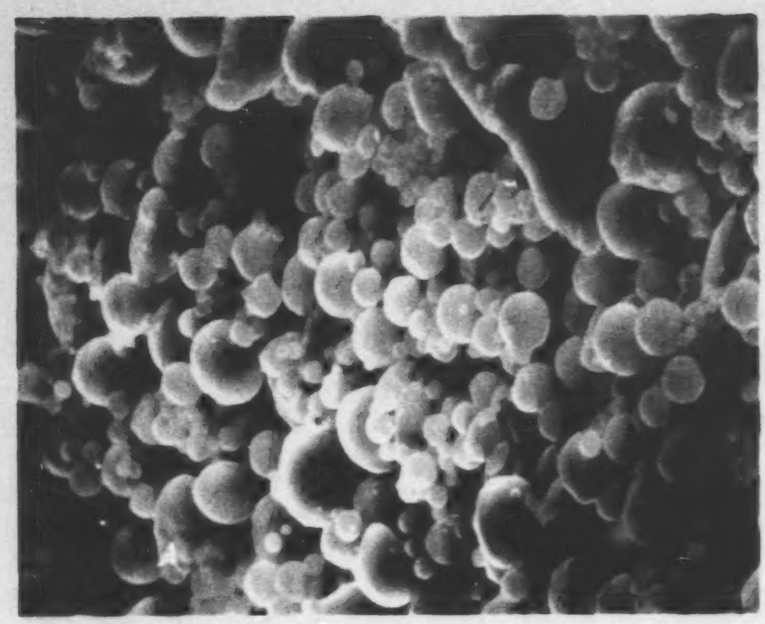

Figure 40. Aluminum test dust.

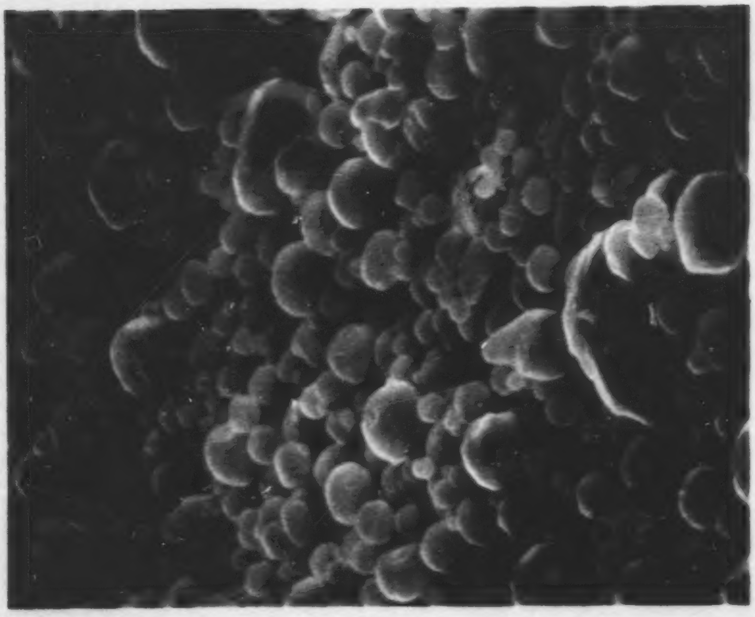

Figure 41. Aluminum dust -- small cyclone cup catch

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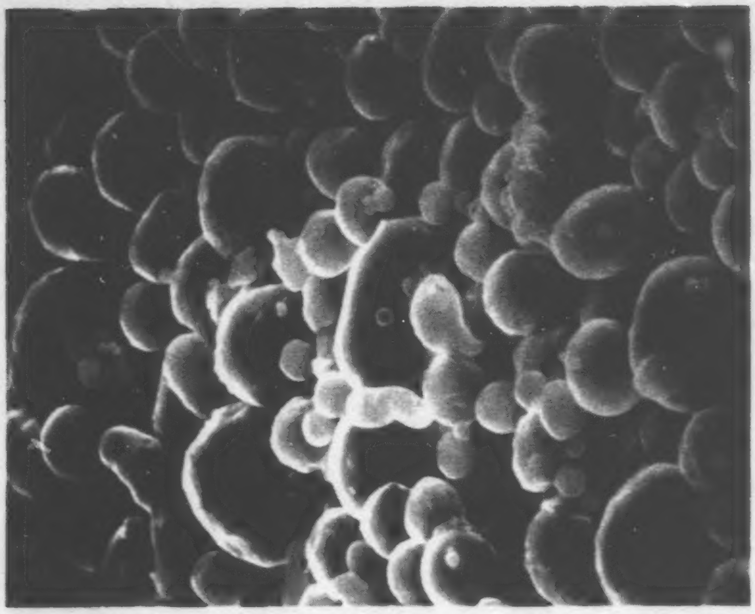

Figure 42. Aluminum dust -- large cyclone cup catch.

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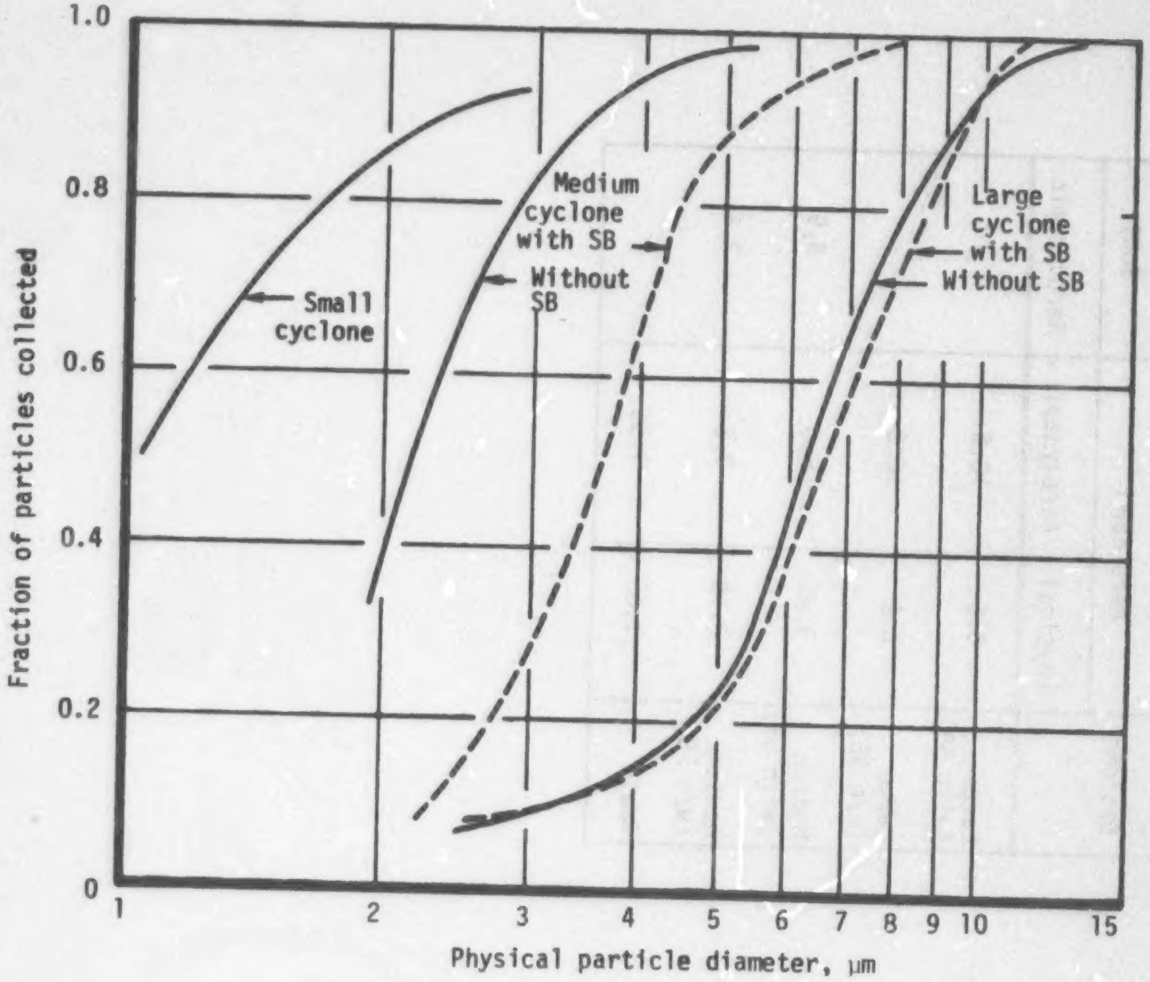

Figure 43. Results of calibration of EPA SASS cyclones.

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TABLE 5. SUMMARY OF CALIBRATION RESULTS

D_{50} Cut Diameter, µm			
Cyclone	Aerotherm		SoRI
	Physical	Aerodynamic	Aerodynamic
Large (with SB)	6.6	10.8	
Large (w/o SB)	6.2	10.2	
Medium (with SB)	3.65	6.0	4.9
Medium (w/o SB)	2.18	3.6	3.5
Small	1.05	1.55	

both physical and aerodynamic diameters. The SoRI D_{50} values for the medium cyclone are shown for comparison. The agreement between the two methods is good.

A second set of SASS cyclones has recently been calibrated by this method. The cyclones tested are a part of a SASS train owned by KVB, Inc. These cyclones were calibrated with the swirl busters removed from the large and middle cyclones. Figure 44 compares the calibration results for the KVB and EPA SASS cyclones. The two cyclone sets compare quite well for the large and medium cyclones, and reasonably well for the small cyclone. This is to be expected, as all of the uncertainty factors in the calibration method -- particle deagglomeration, Coulter counter accuracy, particle uniformity --are more significant for the smaller particle sizes.

Note that Figure 44 correlates cyclone efficiency with physical particle diameter, as measured with the Coulter counter. Table 6 shows the physical and aerodynamic D_{50} cut diameters of the KVB and EPA cyclones. It is interesting to note that the D_{50} aerodynamic cut diameters of the two SASS cyclone sets calibrated are reasonably close -- averaging 9.7, 3.7, and 1.5 µm -- to the desired cut diameters of 10, 3, and 1 µm that were established at the start of the SASS development program.

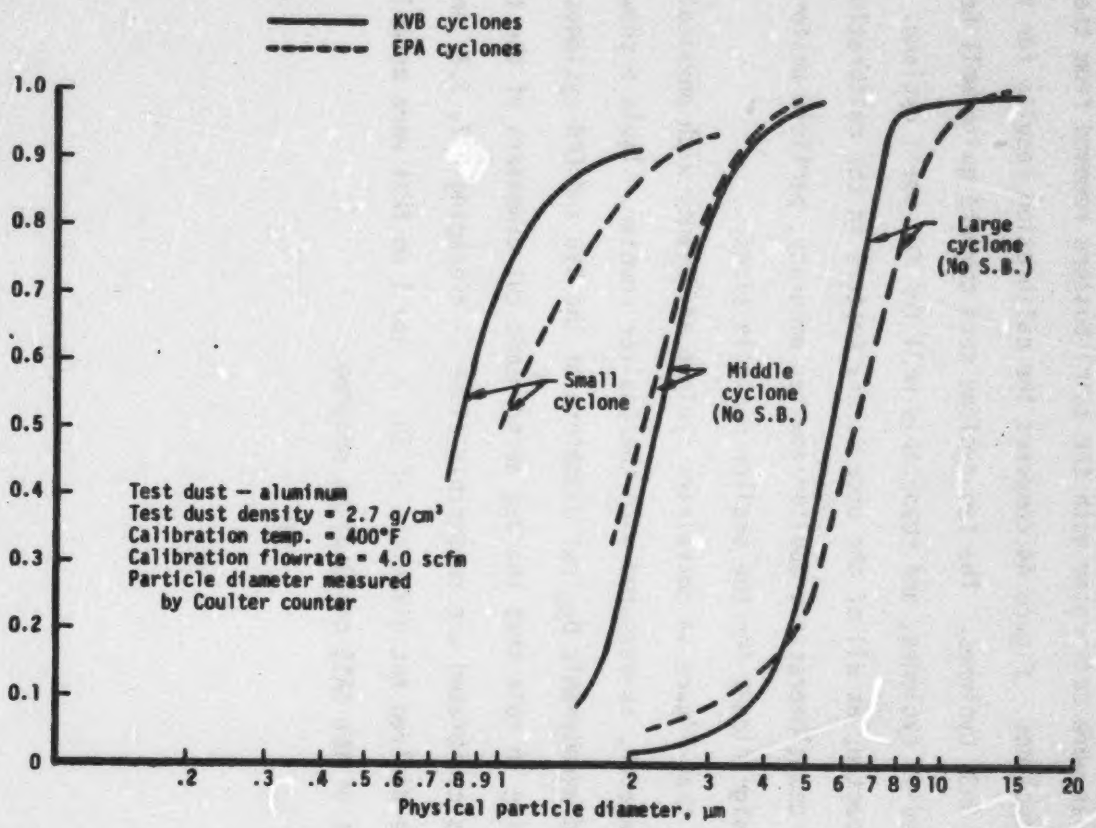

Figure 44. SASS cyclone calibration data.

TABLE 6. COMPARISON -- CALIBRATION RESULTS FOR TWO SETS OF SASS CYCLONES

	D50 Cut Diameters, μm			
	KVB		EPA	
Cyclone	Physical	Aerodynamic	Physical	Aerodynamic
Large[a]	5.61	9.2	6.20	10.2
Medium[a]	2.30	3.8	2.18	3.6
Small	0.81	1.3	1.05	1.7

[a] Swirl busters removed

SECTION 6

SASS MODIFICATIONS AND IMPROVEMENTS

As with any complex instrument, field use has demonstrated the need for changes to ths SASS. Some changes have been accomplished, and some have been recommended and are being studied now. In this section each actual or potential SASS modification is described and discussed.

6.1 FIRST FIELD TESTS

Most of the modifications were the result of comments from the field crews for the first few field tests, which are briefly described below. In all of the field tests, the problems noted were overcome in the field by the test crews, and the desired data was obtained.

Pulverized Coal Furnance Test

This was the first SASS test. It was conducted on the stack of Acurex's pulverized coal-fired furnace before the baghouse on May 24 to 28, 1976. The train used was made by combining one of the incinerator trains with the cyclone/oven section from the CPC train. This produced a SASS nearly identical in design, and functionally equivalent, to current SASS trains. The test was conducted without incident, and cleanup and sample recovery were straight-forward. Figure 45 shows the sampling location. Table 7 shows the particulate collected during the 5-hour test, while Table 8 is the concentration of various elements in the 1-μm cyclone catch, as measured by spark source mass spectroscopy. The fractional organics catch, obtained

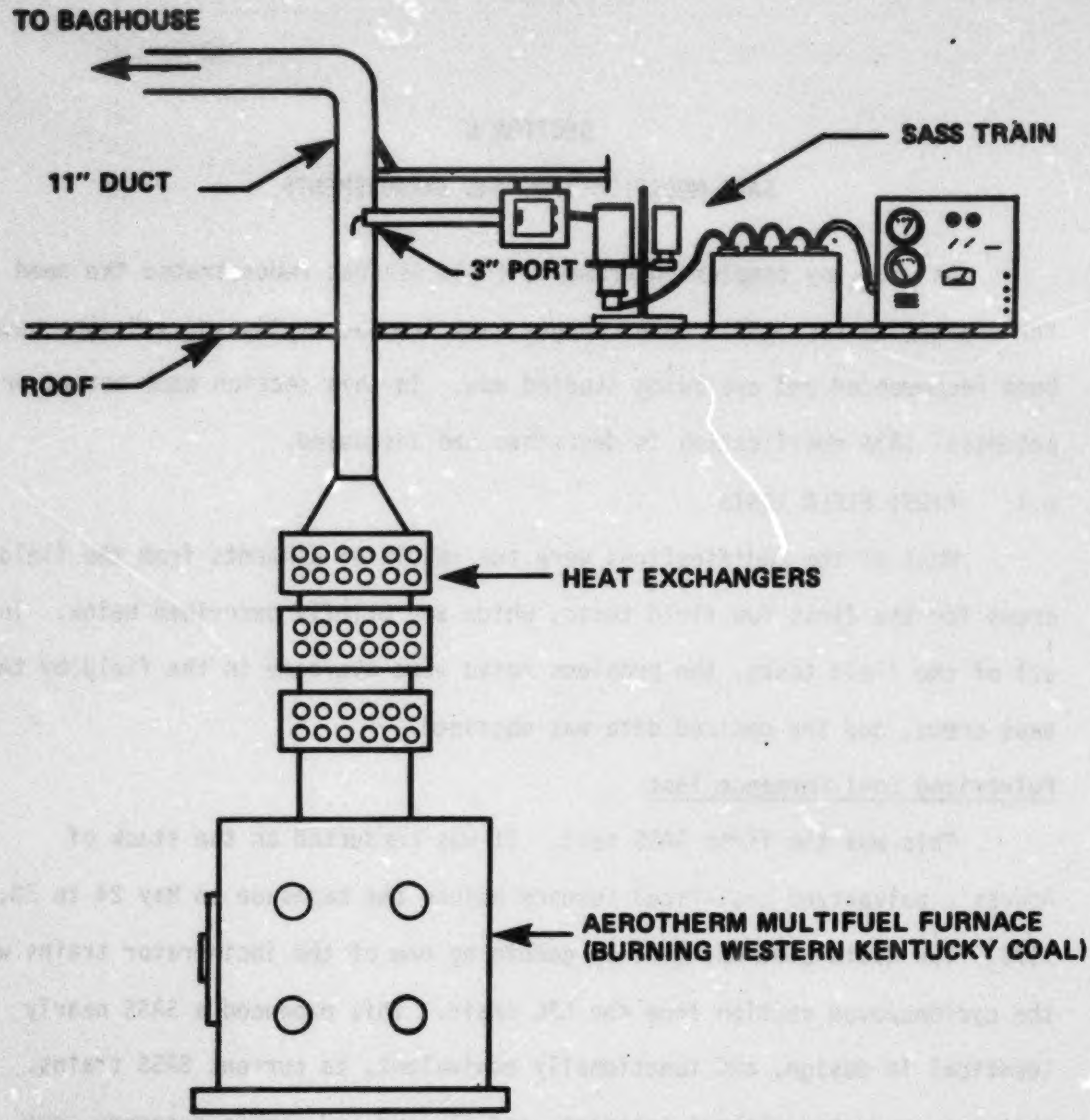
TO BAGHOUSE
SASS TRAIN
11" DUCT
3" PORT
ROOF
HEAT EXCHANGERS
AEROTHERM MULTIFUEL FURNACE
(BURNING WESTERN KENTUCKY COAL)

Figure 45. First SASS test sampling location.

TABLE 7. FIRST SASS TEST -- PARTICULATE CATCH

Fraction	Grams	Percent
Probe + Nozzle	0.35	0.8
10μ Cyclone	14.95	34.7
3μ Cyclone	15.47	35.9
1μ Cyclone	10.15	23.6
Filter	2.16	5.0
		100.0%

TABLE 8. PARTICULATE MATTER IN 1μ CYCLONE -- FIRST SASS TEST (Concentration in ppm weight)

Element	Conc.	Element	Conc.	Element	Conc.	Element	Conc
Uranium	45	Terbium	2	Ruthenium		Vanadium	MC
Thorium	12	Gadolinium	3	Molybdenum	65	Titanium	MC
Bismuth	0.3	Europium	2	Niobium	30	Scandium	68
Lead	95	Samarium	5	Zirconium	420	Calcium	MC
Thallium	20	Neodymium	58	Yttrium	320	Potassium	MC
Mercury	NR	Praseodymium	14	Strontium	310	Chlorine	14
Gold		Cerium	120	Rubidium	560	Sulfur	MC
Platinum		Lanthanum	45	Bromine	0.2	Phosphorus	MC
Iridium		Barium	310	Selenium	3	Silicon	MC
Osmium		Cesium	25	Arsenic	36	Aluminum	MC
Rhenium		Iodine	0.1	Germanium	97	Magnesium	MC
Tungsten	1	Tellurium	≤0.2	Gallium	170	Sodium	MC
Tantalum	≤0.3	Antimony	10	Zinc	MC	Fluorine	≃100
Hafnium	0.7	Tin	8	Copper	150	Oxygen	NR
Lutetium	0.3	Indium	STD	Nickel	220	Nitrogen	NR
Ytterbium	3	Cadmium	3	Colbalt	160	Carbon	NR
Thulium	0.4	Silver	0.5	Iron	MC	Boron	270
Erbium	2	Palladium		Manganese	620	Beryllium	14
Holmium	3	Rhodium		Chromium	400	Lithium	36
Dysprosium	5					Hydrogen	NR

by extracting the sorbent per Level 1 procedures, is shown in Table 9. Table 10 shows GCMS analysis of Fraction 2.

KVB Boiler Test

The second SASS test was on the stack of the KVB, Inc. experimental coal-fired boiler. The test was conducted on July 21 to 22, 1976, using the same train used for the Acurex test. This train used a single vacuum pump and the test was conducted at 4.0 acfm at the cyclones, the standard flowrate at that time. Problems noted included difficulty in disassembling the Swagelock fittings in the cyclone assembly when hot, some dust deposition in an inaccessible spot in the middle cyclone, insufficient strength in the welding of the inlet tube on the small cyclone, some corrosion in the organic module, and bypass of gas due to backflow holes in the impinger stems.

Comanche Power Plant

The stack of the Comanche Power Plant, Colorado Public Service Company, Pueblo, Colorado was tested by Radian Corporation on September 2 to 10, 1976. This SASS test was successfully completed, except for an inability to achieve the desired flowrate through the SASS. The decision was made to supply Radian with another pump and required hoses and valving to allow them to complete their sampling program at 4.0 scfm (6.49 acfm at 400°F).

Radian also reported some difficulty in leak-testing the cyclone assembly and the organic module, and a problem with breakage of the impinger bottles due to interference with the top cap lockdown nuts.

Exxon Miniplant

Battelle Columbus Laboratories used a SASS to sample the Exxon pressurized fluidized bed combustor during the week of February 7, 1977 and again in April 1977. Battelle reported some difficulty in sealing the SASS using

TABLE 9. ORGANIC FRACTIONS FROM TENAX EXTRACT -- FIRST SASS TEST

Fraction	Weight
Fraction 1	28.0 mg
Fraction 2	42.0 mg
Fraction 3	84.0 mg
Fraction 4	72.0 mg
Fraction 5	70.0 mg
Fraction 6	24.0 mg
Fraction 7	<1 mg
Fraction 8	<1 mg

TABLE 10. COMPOUND CLASSES IDENTIFIED IN FRACTION 2

m/e	Compound Class
129	Tetrahydroacenaphthenes
149	Phthalate esters (plasticizers)
153	Acenaphthenes, biphenyls
165	Fluorenes
177	Phenanthrenes
181	Tetrahydrophenanthrenes
205	Tetrahydrofluoranthrenes
227	Chrysenes
251	Benzopyrenes

the Teflon gaskets and O-rings supplied. They also noted considerable evidence of corrosion in the organic module, with a considerable amount of green condensate collected. The condensate was very high in nickel and chromium ion.

6.2 COMPLETED MODIFICATIONS

The various modifications and improvements to the SASS that have been implemented are listed here in approximately chronological order.

Lower Sorbent Temperature

In the original design philosophy for the organic module, the sorbent temperature was to be maintained at 60°C and condensate was to be collected before it reached the sorbent (see Sections 2 and 4.3). Midway through the initial design cycle, EPA directed that the sorbent temperature was to be held at 20°C, and any condensate formed upstream of the sorbent was to be allowed to pass through the sorbent bed. These changes were accomplished before the construction of the first organic module.

Increase Train Flowrate

During the Comanche Power Plant SASS test, Radian Corporation reported they were unable to achieve the desired flowrate of 4.0 scfm with the single-pump train they were using. Communications between Acurex, Radian, and EPA revealed a misunderstanding as to the desired SASS flowrate. Acurex and Southern Research Institute (who were then calibrating the cyclones) had understood the desired flowrate to be 4.0 afm at the cyclones, while Radian had been informed by EPA that the operating flowrate was to be 4.0 scfm. In order to collect a sufficiently large sample within a reasonable sampling time, the SASS flowrate was established at 4.0 scfm. Two major SASS changes were required to increase the train flowrate by some 62 percent. The cyclones, which had been designed for the lower flowrate, would have to be recalibrated and possibly modified. And, because of the increased pressure drop at the higher flowrate, two vacuum pumps operating in parallel would replace the single pump previously used. (The cyclone redesign and calibration efforts are discussed in Section 5.)

A series of laboratory tests at Acurex led to the decision to use two vacuum pumps. The tests demonstrated the capability of a single pump to achieve 4.0 scfm with a clean system, but as the filter loaded up, the increasing pressure drop quickly reduced the flow capacity of the system below 4.0 scfm. The tests were conducted as follows:

A SASS train was assembled in field configuration, including clean fiberglass filter, water in two impinger bottles, but without desiccant. The probe and overn were maintained at 400°F. Separate tests were run with one pump and with two pumps.

In each case, after the operating temperatures were reached, the throttling valve at the pump(s) was opened in steps and the system flowrate noted. When the pump was wide open, maximum system flowrate was achieved. Then in order to simulate an increase in the filter pressure drop, the valve between oven and organic module was closed in steps. This of course reduces system flowrate and increases system Δp. Figure 46 shows the results of these tests. All flowrate data in Figure 46 are corrected to standard conditions (29.92 in. Hg., 70°F). As can be seen, the maximum flowrate attainable is the operating zone. With a single pump, 4.0 scfm can be maintained between 9 in. Hg. (the Δp for a clean system) and 15 in. Hg. With two pumps, the operating zone is between 9 and 21.5 in. Hg.

In subsequent field tests, two vacuum pumps have provided sufficient capacity for accomplishing Level 1 sampling.

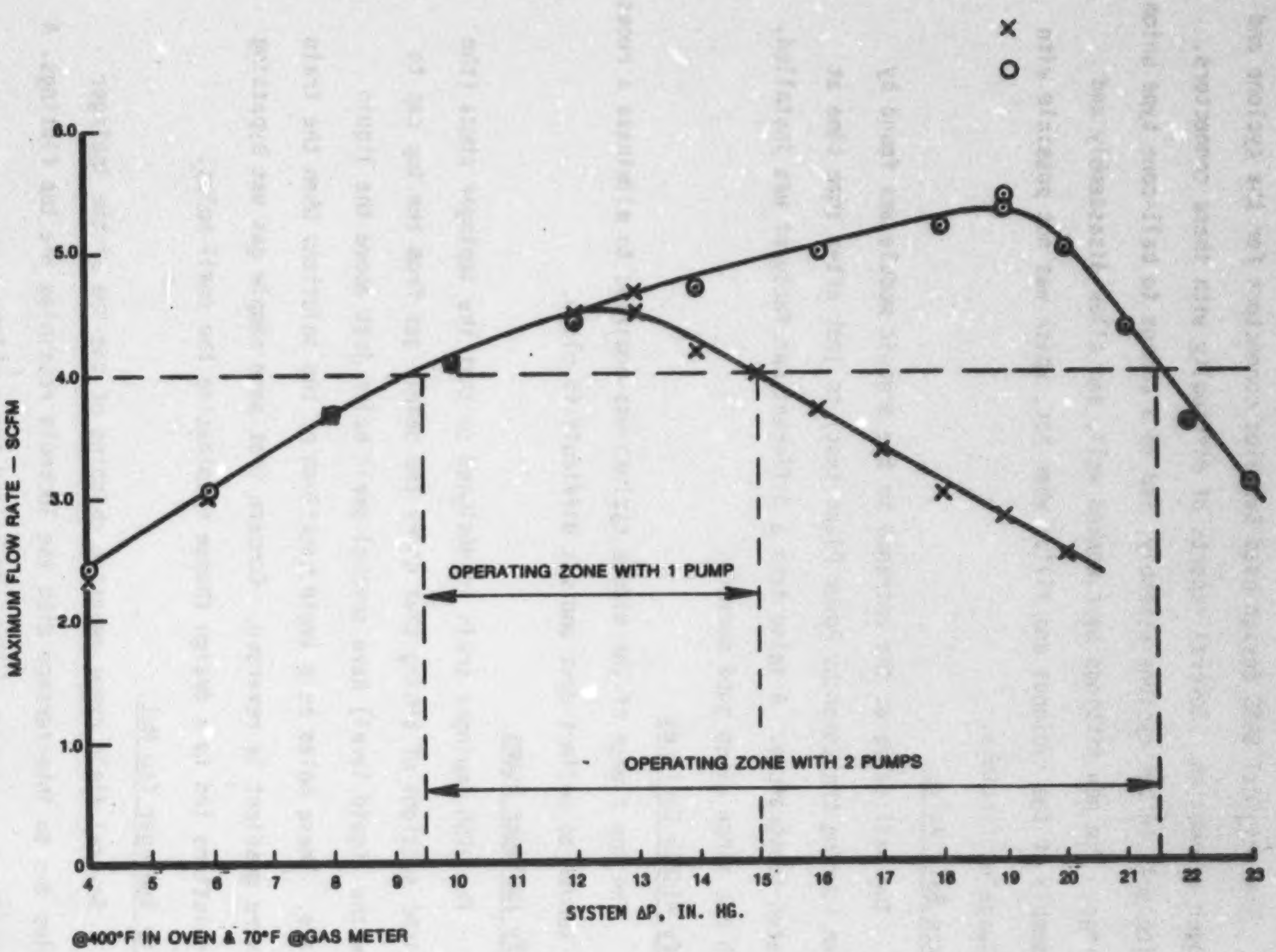

Figure 46. Vacuum pump characteristic curves.

Replace Component Connectors

The original SASS design used Swageloc connectors for the cyclone and impinger assemblies. Several reports of difficulty with these connectors, particularly in the cyclone assembly, led to a change to ball-cone type union fittings. The new fittings have worked well, and allow disassembly and reassembly of the cyclones and filter when hot, which was not possible with the Swageloc fittings.

Replace Ball Valve

The ball valve at the entrance to the organic module was found by Radian (during the Comanche Power Plant test) to leak after some time at elevated temperature. A valve from a different manufacturer was installed, which has since given good service.

Modify Middle Cyclones

The top flange of the middle cyclone was modified to eliminate a recess that tended to collect dust and was difficult to clean.

Modify Impinger Stems

The HVSS impinger train is designed so that the impinger stems (the straight sections of tubing that carry the sample gas from the top cap to below the liquid level) have several small holes just above the liquid surface. These holes help avoid backflush of the solutions when the train pressure gradient is reversed. Concern that some sample gas was bypassing the solutions led to a design change eliminating the small holes.

Modify Impinger Cap Nut

Several field crews reported chipping of the top of the impinger bottles due to interference with the locknuts retaining the top fittings. A modified nut was designed that eliminated the problem.

Change Seal Material

There were many reports of problems in getting a satisfactory leak check using the Teflon gaskets and O-rings originally designed for the SASS. The Teflon seals seemed to work satisfactorily for experienced crews using new seals. With the first use, however, the Teflon acquires a permanent set that makes reuse problematical. It was recognized that a seal material other than Teflon would best solve the problem. The basic prohibition of any materials except 316 stainless steel, Teflon, and Pyrex glass for use in the SASS required thorough testing of alternate seal material candidates.

After testing at EPA, Acurex, and Arthur D. Little, Viton A was approved for SASS use, although Teflon is still the seal material of choice when it can be used. Official approval was received from EPA on May 27, 1977. Viton has worked well to solve the leak problems, but it seems to stick to train surfaces when heated making disassembly difficult. Teflon-coated Viton seals are now being evaluated.

Oven Wiring Change

Some problems with shorts in the oven electrical system were traced to faulty installation of electrical wires in the oven base. Assembly procedures were changed to eliminate the problem, and existing SASS owners were notified of a simple field fix.

Modified Sorbent Cartridge

The original sorbent cartridge, which was designed to be assembled with force-fit crimp rings, was redesigned with a screw-thread fitting for easier assembly/disassembly. This change is discussed in Section 5.2.

Impinger Connector Tube Clamps

There are three 1/2-inch tubes that interconnect the impinger bottles, and carry sample gas from one bottle to the next. In the original SASS design, rigid stainless steel tubes, bent into a U-shape, were used. These performed adequately, but their rigidity tended to cause leaks at the impinger top cap fittings if the impinger bottles were turned or twisted. Also, with the rigid tubes the entire impinger assembly was fixed and movement at any single part was generally not possible. For example, in order to change the desiccant, the entire impinger assembly had to be removed from the ice bath, worked on, and then be carefully leak tested before resuming operation.

To overcome these problems, flexible metal bellows were substituted in December 1976. These made operation of the train much easier. Subsequent field experience showed evidence of corrosion in the bellows at locations where the bellows construction left crevices where oxygen depletion could occur. Also, some difficulty was experienced in cleaning the bellows.

In September 1977, an impinger assembly using flexible corrugated Teflon tubing was constructed by Acurex and field-tested by TRW. They reported excellent field performance, with very easy post test cleanup. These Teflon connectors have been approved for Level 1 SASS use by EPA, and are now being made available to SASS owners.

Oversized Filter Holder

When sampling a source with a high particulate loading, it may be necessary to replace the filter two or more times during a 5-hour Level 1 SASS test. Since the filter holder is hot (400°F), changing the filter is a difficult and time-wasting procedure. Acurex designed an oversized filter holder with about 2-1/2 times the surface area of the standard filter holder. The oversized filter holder is compatible with existing SASS trains, and will eliminate filter changes during most Level 1 tests. The oversized filter holders were evalutated by TRW and SoRI with field tests; performance was excellent. The oversized filter holders have been made available to SASS owners.

Eliminate Spun Flanges on Medium Cyclone

The original cyclone design included a spun flange on the top of the 3-μm cyclone. This flange was thin and subject to bending. A welded-on machined flange has been substituted.

Eliminate Crevice in Organic Module

Corrosion was noted in a crevice at the bottom of the condensate collection section of the organic module. The welding technique was modified to eliminate the crevice.

6.3 POTENTIAL SASS MODIFICATIONS

Several recommendations for SASS changes have been made that have not yet been implemented. All suggestions received to date are listed below, in no particular order:

- The cyclones are difficult to get at in the oven. Replumb so fittings can be more easily reached. Consider moving inlet and outlet holes in the oven walls so cyclone assembly is reversed and the small cyclone is in front
- Consider an alternative to the aircraft-type clamps to eliminate cut fingers by sampling crew members, and to improve sealing
- Use thicker metal in the cyclones so they are more sturdy
- Put index marks on the cyclones to allow easier assembly
- Design a jig to hold the cyclones outside the oven to allow assembly and leak checking. The cyclone assembly could then be inserted into the oven and connected using just the probe and filter fittings.

- Battalle reports erosion at the center of the filter paper. Consider a design with a tapering inlet to reduce the entering velocity.
- Consider rhodium plating the inside of the organic module to eliminate corrosive attack. Will require concentric (non scrapping) construction.
- Consider ways to improve the concentricity of the gas cooler section of the organic module. Eliminate welds by boring heavy wall tubing or spinning small tubing up to size.
- The nut at the gas outlet tube of the organic module interferes with the Marmon clamp. Fix by moving or lengthening tube.
- Design a glass/teflon organic module to eliminate corrosion. Keep existing temperature control section.
- Design a combined XAD-2 and condensate reservoir section (eliminate the lowest clamp on the organic module)
- Increase the size of the impinger case. Insulate the case to reduce ice use.
- Provide a draincock at the bottom of the impinger case
- Design heavier cyclone collection cups that are less likely to be bent
- Provide an extra thermocouple to monitor the ice bath temperature
- Redesign the condensate bottle and adaptor for less fragility and easier use
- Provide a level gage on the condensate reservoir

- If the pressure drop can be tolerated, install check valves in the impinger connector tubes to eliminate backflow
- Provide isokinetic sampling capability by adding an "Isokinetic Module," described in Appendix B

APPENDIX A

CYCLONE CALIBRATION DATA ANALYSIS

For a cyclone, the collection efficiency as a function of particle size ($\eta(r)$) can be calculated from

$$\eta(r) = \frac{M_c(r)}{M_f(r)} \qquad (1)$$

where $M_c(r)$ is the mass of particles of size r collected by the cyclone during some time interval and $M_F(r)$ is the total mass of particles of size r introduced into the cyclone during the same time interval. Thus a series of tests with different sized monodisperse dust could be used to establish the collection efficiency of a cyclone. It is more common, however, to test the cyclone with a polydisperse dust. In this case the available information is the size distribution of the collected and input dust. This is commonly presented as the mass fraction of the dust with size less than (or greater than) size r. If f(r) represents the size distribution, then M(r) is given by:

$$M(r) = M \; \frac{df(r)}{dr} \; dr \qquad (2)$$

where M is the total mass of the sample. Equation (1) then becomes:

$$\eta(r) = R \, \frac{df_c(r)}{dr} \bigg/ \frac{df_F(r)}{dr} \qquad (3)$$

where R is the ratio of the mass collected to the total feed mass. Therefore, if the size distribution of the feed and the collected dust are available at discrete values of r, Equation (3) can be evaluated by numerical differentiation of the two size distributions.

The accuracy of numerical differentiation is sensitive to the degree of curvature of the function, the number of discrete points used to represent the function and the technique used to calculate the derivative. These three features are discussed in the following paragraphs.

Table 11 and Figures 47 and 48 show typical size distribution for feed and collected dusts. Figure 47 is on a standard linear scale; whereas Figure 48 is on log-probability paper. The importance of this type of plot is that a normal (Gaussian) distribution will appear as a straight line. Many dust samples are almost normally distributed. In general it is easier to obtain accurate numerical deviation from near-linear curves then from highly curved ones. In this case both figures exhibit a nearly linear nature except near the ends of the curve in Figure 47. Therefore deviations calculated near the ends of the curve in Figure 47 would be more sensitive to the number of data points and the calculated procedure than those of Figure 48.

Transformation to the log-probit coordinates of Figure 48 offers improvement to the accuracy of the numerical derivatives.

This transformation is given by:

$$\begin{aligned} y &= \text{probit}\ (f) \\ x &= \ln r \end{aligned} \qquad (4)$$

where probit (f) is defined by:

TABLE 11. SIZE DISTRIBUTION OF FEED AND COLLECTED DUST

Particle size (microns)	f_C	f_{Filter}	f_F
0.794	0	0.003	0.00169
1.0	0	0.0	0.00562
1.26	0	0.02	0.0112
1.587	0	0.041	0.023
2.0	0	0.078	0.0438
2.52000	0.00500	0.13900	0.08031
3.17500	0.01600	0.2270	0.13458
4.00000	0.04700	0.39400	0.24201
5.04000	0.10800	0.64300	0.40867
6.35000	0.30900	8.7200	0.62541
8.00000	0.55700	0.97500	0.79192
10.07900	0.76100	0.99500	0.89251
12.69900	0.87900	1.00000	0.94700
16.00000	0.94100	1.00000	0.97416
20.15900	0.97900	1.00000	0.99080
25.39800	0.99100	1.00000	0.99606

Definitions:

f_C - mass fraction of collected dust with diameter less than r

f_{Filter} - mass fraction of dust with size less than r that is collected on a filter at the outlet of the cyclone.

f_F - mass fraction of dust with size less than r in the feed. Calculated from mass conservation principles: $f_F(r) = Rf_C(r) + (I-R)\, f_{Filter}(r)$, where R = total mass fraction of dust collected.

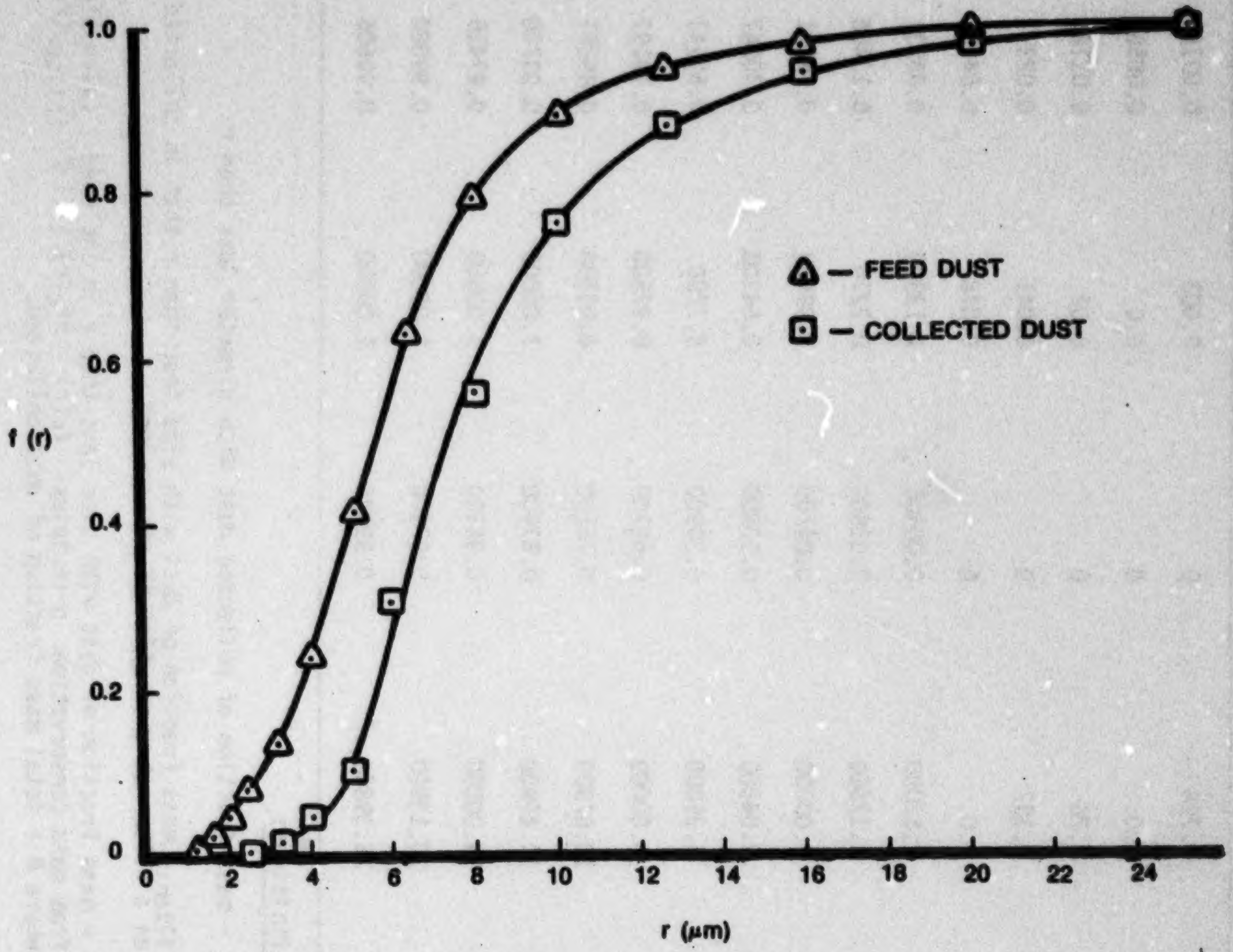

Figure 47. Curve of distribution of feed and collected dust.

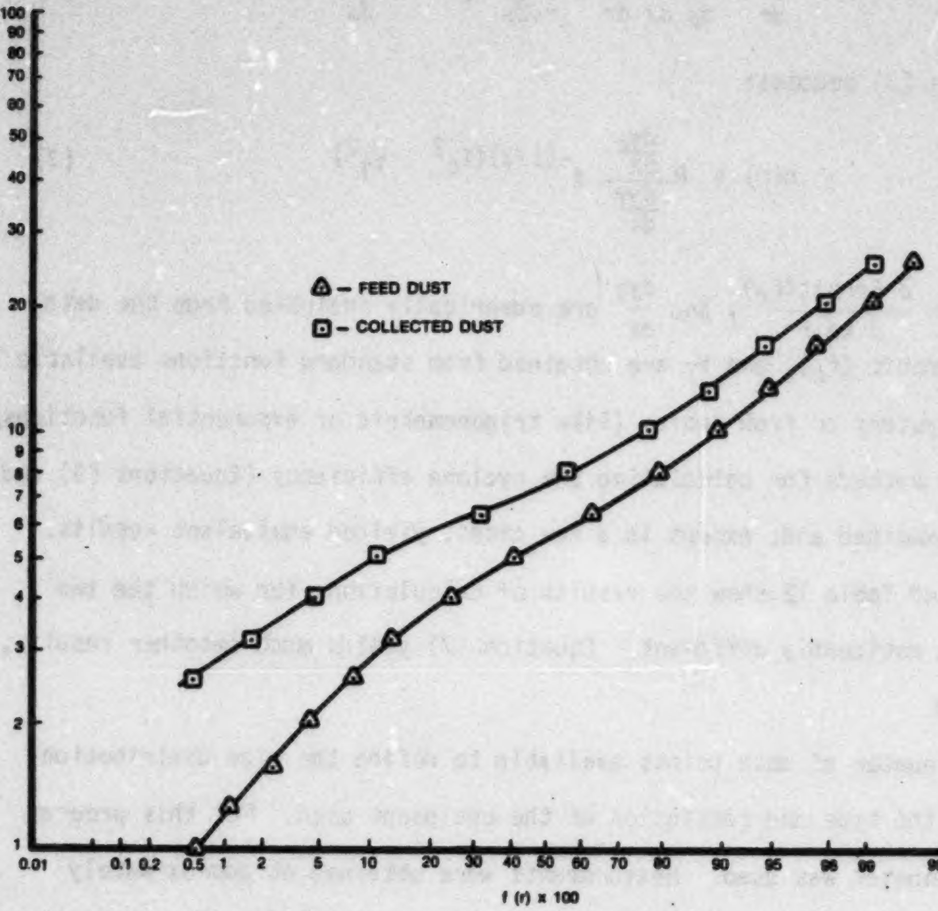

Figure 48. Curve of feed and collected dust (log — probability plot).

$$f = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\text{probit}(f)} e^{-1/2\, t^2}\, dt. \tag{5}$$

Then (df/dr) is given by:

$$\frac{df}{dr} = \frac{df}{dy}\,\frac{dy}{dx}\,\frac{dx}{dr} = \frac{1}{r\sqrt{2\pi}}\, e^{-y^2/2}\,\frac{dy}{dx} \tag{6}$$

and Equation (3) becomes:

$$n(r) = R\,\frac{\frac{dy_C}{dx}}{\frac{dy_T}{dx}}\, e^{-(1/2)(Y_C{}^2 - Y_T{}^2)} \tag{7}$$

where $\frac{dy_C}{dx}$ $\left(= \frac{d\ \text{Probit}(f_C)}{d\ \ell n\ r}\right)$ and $\frac{dy_T}{dx}$ are numerically evaluated from the data and y_C (= Probit (f_C)) and Y_T are obtained from standard functions available on most computers or from tables (like trigonometric or exponential functions).

Both methods for calculating the cyclone efficiency (Equations (3) and (7)) were examined and, except in a few cases, yielded equivalent results. Figure 49 and Table 12 show the results of calculations for which the two methods are noticeably different. Equation (7) yields much smoother results, as expected.

The number of data points available to define the size distribution depends on the type and resolution of the equipment used. For this program a Coulter counter was used. Measurements were obtained at approximately equal intervals of log r. Table 11 presents the distribution data for curves in Figure 47 and 48. Enough measurements must be taken to define the linear mid-range (see Figure 47) and the curved regions near the ends. If few data points are available to define the curved region, the transformation to the more linear form (log-Probit) becomes more necessary.

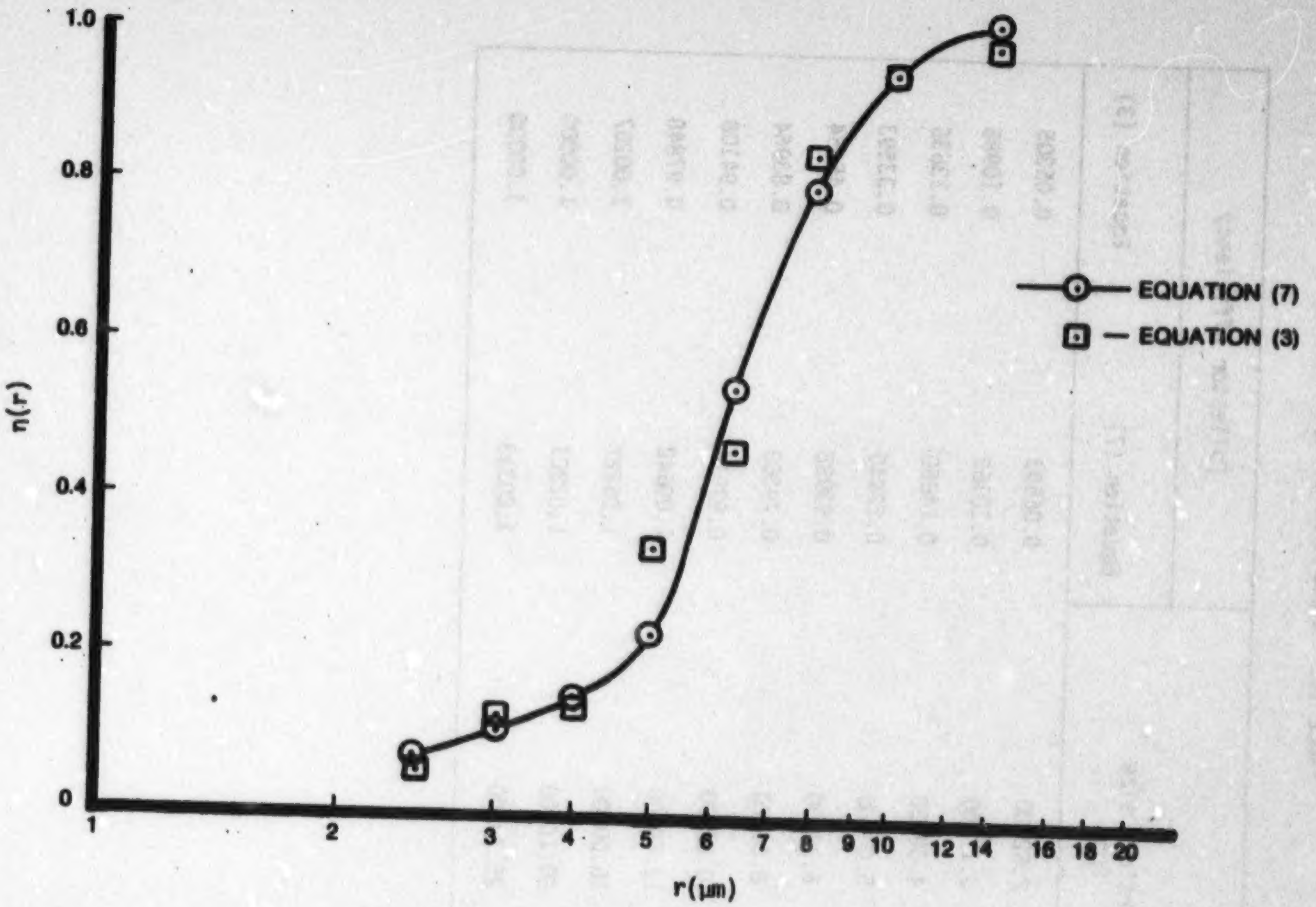

Figure 49. Comparison of cyclone collection efficiency calculated from Equations (3) and (7).

TABLE 12. CALCULATED CYCLONE EFFICIENCY

Particle size (µm)	Collector Efficiency	
	Equation (7)	Equation (3)
2.52000	0.06593	0.05305
3.17500	0.10162	0.10985
4.00000	0.14050	0.13635
5.04000	0.22840	0.33593
6.35000	0.53988	0.45654
8.00000	0.79362	0.83964
10.07900	0.93936	0.94108
12.69900	1.00642	0.97848
16.00000	1.05227	1.00207
20.15900	1.02801	1.00000
25.39800	1.00333	1.00000

There are numerous ways to compute numerical derivatives. Several are listed below:

- Linear fit between points; compute derivates at a point from the average of slopes to the adjacent points
- Quadratic curve fit through the three nearest points; compute derivatives at a point from the slope of the quadratic through the point and the two adjacent points
- Weighted quadratic curve fit if using the points on either side and a centered quadratic
- Higher order polynomial curve fits
- Transcendental function curve fits
- Weighted linear curve fits using four or five adjacent points

All of these offer advantages or disadvantages for particular shapes of curves. In the present analysis, the first three methods were considered. This choice was based on the degree of linearity of the data. Method 2 gave the most consistent results. This is probably a result of the "smoothing" of data inhererent in the method.

A listing of the computer program written to process the dust distribution data and calculate cyclone efficiencies is given in Table 13. Tables 14 and 15 show a listing of the input data and the output corresponding to the example given in the Figures 47, 48, and 49.

TABLE 13. PROGRAM FOR CALCULATING CYCLONE EFFICIENCY

```
11/18/77  09:42:06 PTD    0289AA343    000289         S29   20


FE               COMON PROC
                       PARAMETER    P=50
                       COMMON  /LIMVAR/
                     * FF(P),FCUP(P),XF(P),XCUP(P),SF(P),SCUP(P),EFF(P),R(P),EF(P),
                     * DFI(P),DFC(P)
                       COMMON  /CONST/
                     * N,RATIO,ISLOP
                  END
```

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TABLE 13. Continued

```
      INCLUDE COMON
C     *****
C
      CALL INPUT
C
C     *****
C
C     FIND SLOPES FOR R VS F
C
      IF (ISLOP.EQ.0) GO TO 5
      CALL SGETR(N,R,FF,DFI)
      CALL SGETR(N,R,FCUP,DFC)
      DO 1 I=1,N
         EF(I)=RATIO*DFC(I)/DFI(I)
    1 CONTINUE
    5 CONTINUE
C
C     LOOK UP PROBITS
C
      DO 10 I=1,N
         CALL MONRIS (FF(I),XF(I),NN)
         R(I)=ALOG(R(I))
         CALL MONRIS (FCUP(I),XCUP(I),NN)
   10 CONTINUE
C
C     FIND SLOPES FOR PROBIT VS LOGN F
C
      CALL SGETR(N,XF,R,SF)
      CALL SGETR(N,XCUP,R,SCUP)
C
C     CALCULATE EFFICIENCY
C
```

TABLE 13. Continued

```
      DO 20 I=1,N
         E=EXP((XF(I)**2-XCUP(I)**2)/2.)
         EFF(I)=RATIO*SF(I)/SCUP(I)*E
   20 CONTINUE
C     *****
C
      CALL OUTPUT
C
C     *****
      END
```

TABLE 13. Continued

```
      SUBROUTINE INPUT
      INCLUDE COMON
      DIMENSION RECORD(18)
      READ (5,1) (RECORD(I),I=1,18)
      WRITE(6,1) (RECORD(I),I=1,18)
    1 FORMAT (18A4)
C
C     N=NO. OF PTS., IGT=1 FOR F.GT.R, IFILT=1 FOR FILTER
C
      READ (5,10) N,IGTF,IGTC,IFILT,ISLOP
   10 FORMAT (12I5)
      WRITE (6,20) N,IGTF,IGTC,IFILT,ISLOP
   20 FORMAT (/2X,2HN=,I3,2X,5HIGTF=,I3,2X,5HIGTC=,I3,2X,6HIFILT=,I3,2X,
     *6HISLOP=,I3/)
C
C     RATIO=MCUP/MFEED
C
      READ (5,30) RATIO
   30 FORMAT (7F10.5)
```

TABLE 13. Continued

```
      WRITE (6,40) RATIO
   40 FORMAT (/2X,22HMASS CUP / MASS FEED =,F10.5/)
      IF(IFILT.EQ.1) WRITE (6,45)
   45 FORMAT (/,2X,5H*****//,2X,6HFILTER//,2X,5H*****/)
      IF(IGTF.EQ.1) WRITE (6,50)
   50 FORMAT (/,2X,49HINPUT PERCENTS HAVE BEEN CHANGED TO % LESS THAN R/
     *)
      WRITE (6,60)
   60 FORMAT (/4X,1HI,2X,10HR(MICRONS),2X,5HFF(I),3X,7HFCUP(I)/)
C
C     INPUT R IN MICRONS
C
      DO 65 I=1,N
         READ (5,30) R(I),FF(I),FCUP(I)
         IF (IGTF.EQ.1) FF(I)=100.-FF(I)
         IF (IGTC.EQ.1) FCUP(I)=100.-FCUP(I)
         FF(I)=FF(I)*.01
         FCUP(I)=FCUP(I)*.01
         WRITE (6,70) I,R(I),FF(I),FCUP(I)
   65 CONTINUE
   70 FORMAT (2X,I3,7F10.5)
      IF (IFILT.EQ.0) GO TO 90
      WRITE (6,75)
   75 FORMAT (/2X,5H*****//,2X,4HFEED//,2X,5H*****/)
      WRITE (6,60)
C
C     CHANGE FILTER TO INPUT DUST
C
      DO 80 I=1,N
         FF(I)=RATIO*FCUP(I)+(1.-RATIO)*FF(I)
         WRITE (6,70) I,R(I),FF(I),FCUP(I)
   80 CONTINUE
   90 CONTINUE
      RETURN
      END
```

TABLE 13. Continued

```
      SUBROUTINE OUTPUT
      INCLUDE COMON
      WRITE (6,10)
   10 FORMAT (/34X,25H*************************//42X,6HOUTPUT,//34X,25H*
     ************************/)
      WRITE (6,20)  RATIO
   20 FORMAT (/2X,22HMASS CUP / MASS FEED =,F10.5/)
      IF (ISLOP.EQ.0) GO TO 29
      WRITE (6,25)
   25 FORMAT(/2X,38HCOLLECTION EFFICIENCY BASED ON DFC/DFI,/3X,28HI     D
     *FC        DFI         EFF/)
      DO 28 I=1,N
         WRITE (6,60) I,DFC(I),DFI(I),EF(I)
   28 CONTINUE
   29 CONTINUE
      WRITE (6,30)
      WRITE (6,40)
   30 FORMAT (//3X,60H1 PARTICLE COLLECTOR     FEED    COLLECTOR     FEED
     * COLLECTOR)
   40 FORMAT (3X,59H  SIZE(MIC)    EFF        SLOPE      SLOPE      PROBIT
     * PROBIT/)
      DO 50 I=1,N
         R(I)=EXP(R(I))
         WRITE (6,60) I,R(I),EFF(I),SF(I),SCUP(I),XF(I),XCUP(I)
   50 CONTINUE
   60 FORMAT (I4,8F10.5)
      RETURN
      END
```

TABLE 13. Continued

```
      SUBROUTINE SGETR(L,X,Y,EM)
      DIMENSION    X(10),Y(10),EM(10)
      JM=1
      I=1
      A3=X(2)-X(1)
      B3=Y(2)-Y(1)
      A4=X(3)-X(2)
      B4=Y(3)-Y(2)
      S34=A3*B4-A4*B3
      A2=A3
      A1=A3
      DB=2.*A3*S34/A4/(A3+A4)
      B2=B3-DB
      B1=B2-DB
      S12=A1*B2-A2*B1
      S13=A1*B3-A3*B1
      S24=A2*B4-A4*B2
      S23=A2*B3-A3*B2
      GO TO 9
    4 DO 6 I=2,L
      A2=A3
      A3=A4
      B2=B3
      B3=B4
      S12=S23
      S13=S24
```

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TABLE 13. Continued

```
      S23=S34
      IF(I-L+1) 20,7,19
   20 A4=X(I+2)-X(I+1)
      B4=Y(I+2)-Y(I+1)
    5 S24=A2*B4-A4*B2
      S34=A3*B4-A4*B3
      J1=2
      GO TO 9
    6 CONTINUE
      GO TO 18
    7 A4=A3
      A1=A3
      DB=2.*A3*S23/A2/(A2+A3)
      B4=B3+DB
      B1=B4+DB
      GO TO 5
   19 A4=A1
      B4=B1
      GO TO 5
    9 IF(S23) 11,10,11
   10 TN=B2/A2
      GO TO 17
   11 IF(ABS(S12)+ABS(S13)) 10,10,12
   12 IF(ABS(S24)+ABS(S34)) 10,10,13
   13 IF(ABS(S12)+ABS(S34)) 15,15,14
   14 IF(ABS(S24)+ABS(S13)) 15,15,16
   15 TN=(B2+B3)/(A2+A3)
      GO TO 17
   16 S2=S12*S24
      S3=S13*S34
      IF(S2*S3.LT.0.) S3=-S3
      CB=S2*A3*A3
      DB=S3*A2*A2
      B=S2*A3*B3-S3*A2*B2
```

TABLE 13. Concluded

```
      IF(CH-DB) 22,25,22
   25 A=S2*B3*B3-S3*B2*B2
      TN=A/B*0.5
      GO TO 17
   22 A=CH-DB
      D=ABS(S23)*SQRT(S2*S3)
      TN=(B+D)/A
      IF((A2*TN-B2)*(B3-A3*TN).LE.0.) TN=(B-D)/A
   17 EM(I)=TN
      GO TO (4,6),JM
   13 RETURN
      END
```

TABLE 14. LISTING OF INPUT FOR THE EXAMPLE PROBLEM IN FIGURES 1 THROUGH 3

```
          RUN 19    FILTER[a]
           11     1     1     1     1
      .438
        2.520    86.1        99.5
        3.175    77.3        98.4
        4.000    60.6        95.3
        5.040    35.7        89.2
        6.350    12.8        69.1
        8.000     2.5        44.3
       10.079     0.5        23.9
       12.699     0.0        12.1
       16.000     0.0         5.9
```

[a] The input for this problem consisted of collector (cyclone cup) and filter (cyclone exit) distributions given in percent of mass greater than size r.

TABLE 15. PROGRAM OUTPUT FOR THE SAMPLE PROBLEM

```
RUN 19   FILTER

N= 11  IGTF=  1  IGTC=  1  IFILT=  1  ISLOP=  1

MASS CUP / MASS FEED =     .43800


*****

FILTER

*****


INPUT PERCENTS HAVE BEEN CHANGED TO % LESS THAN R


  I   R(MICRONS)   FF(I)[a]  FCUP(I)[b]

  1    2.52000     .13900     .00500
  2    3.17500     .22700     .01600
  3    4.00000     .39400     .04700
  4    5.04000     .64300     .10800
  5    6.35000     .87200     .30900
  6    8.00000     .97500     .55700
  7   10.07900     .99500     .76100
  8   12.69900    1.00000     .87900
  9   16.00000    1.00000     .94100
 10   20.15900    1.00000     .97900
 11   25.39800    1.00000     .99100

*****

FEED

*****


  I   R(MICRONS)   FF(I)[c]  FCUP(I)

  1    2.52000     .08031     .00500
  2    3.17500     .13458     .01600
  3    4.00000     .24201     .04700
  4    5.04000     .40867     .10800
  5    6.35000     .62541     .30900
  6    8.00000     .79192     .55700
```

[a] Filter dust

[b] Collected (cup) dust

[c] Feed dust

TABLE 15. Concluded

```
  7  10.07900       .89251      .76100
  8  12.69900       .94700      .87900
  9  16.00000       .97416      .94100
 10  20.15900       .99080      .97900
 11  25.39800       .99606      .99100

                                                  **************************

                                                           OUTPUT

                                                  **************************


MASS CUP / MASS FEED =      .43800


COLLECTION EFFICIENCY BASED ON DFC/DFI
 I     DFC         DFI        EFF

 1    .00746      .06159     .05305
 2    .02700      .10767     .10965
 3    .04681      .15036     .13635
 4    .12478      .16269     .33593
 5    .15183      .14567     .45654
 6    .13721      .07157     .83964
 7    .06891      .03207     .94108
 8    .02897      .01297     .97848
 9    .01328      .00581    1.00207
10    .00562      .00246    1.00000
11   -.00147     -.00065    1.00000


 I PARTICLE COLLECTOR      FEED   COLLECTOR    FEED   COLLECTOR
   SIZE(MIC)   EFF        SLOPE     SLOPE     PROBIT    PROBIT

 1   2.52000     .06593     .86398     .55665  -1.40300  -2.57583
 2   3.17500     .10162     .65951     .52517  -1.10499  -2.14441
 3   4.00000     .14050     .52767     .51706   -.69984  -1.67466
 4   5.04000     .22840     .46811     .42886   -.23097  -1.23723
 5   6.35000     .53988     .45309     .34163    .31971   -.49869
 6   8.00000     .79362     .50265     .38214    .81309    .14337
 7  10.07900     .93936     .57666     .45093   1.23998    .70952
 8  12.69900    1.00642     .63940     .51833   1.61645   1.17000
 9  16.00000    1.05227     .64170     .52258   1.94576   1.56322
10  20.15900    1.02801     .70360     .61061   2.35755   2.03352
11  25.39800    1.00333     .66188     .78211   2.65700   2.36562

"FIN
```

APPENDIX B

ISOKINETIC SASS TRAIN CONCEPTUAL DESIGN

Introduction

The SASS, as now designed, maintains a constant flowrate at the cyclones to assure a constant D_{50} cut diameter. As a result, it is not possible to continually vary the train flowrate to maintain isokinetic sampling at the nozzle, as is done with Method 5 particulate sampling trains. For Level 1 sampling with the SASS, the usual procedure is to choose a nozzle size from those available that gives the closest approximation to isokinetic sampling. An "expected average" duct velocity is used. Isokinetic velocity mismatch can usually be held to less than 20 percent when duct velocity is constant during the test. If duct velocity varies, the mismatch can be greater.

For particles less than about 5-µm aerodynamic diameter, the levels of isokinetic mismatch experienced with the SASS are probably not significant. For larger particles, or for widely varying duct velocities, nonisokinetic sampling may introduce significant errors.

Recognizing this potential problem, EPA/RTP authorized Acurex to briefly investigate ways to modify the SASS to make it capable of true isokinetic sampling, while maintaining constant flow at the cyclones. Only concepts involving flowrate variation were considered. (A report was prepared and submitted to EPA in June 1977.)

Possible Approaches

The basic problem is to maintain a fixed flowrate through the SASS train cyclones (4.0 scfm = 6.49 acfm at 400°F), while at the same time varying the sampling velocity at the nozzle to adjust to varying stack gas velocities. Four different ways of doing this were considered; these are described below.

In-Stack Velocity Control

In this concept, the flowrate through the entire train is kept constant at 4.0 scfm, while the velocity of the stack gas near the nozzle is adjusted. Figure 50 illustrates the concept. The sampling nozzle is surrounded by a large shroud that sucks in stack gas at a constant flowrate so the nozzle is sampling isokinetically. Variations in the stack gas velocity are automatically corrected for by the design of the system.

Figure 50 shows a representative set of flow streamlines, assuming the velocity through the shroud is substantially higher than the stack velocity. The flow streamlines are badly distorted near the periphery of the shroud, but are nearly straight at the center of the shroud (where the sampling nozzle is located). Thus, the stack gas entering the nozzle contains an undistorted distribution of stack gas particulate. A similar situation occurs when the stack gas velocity is higher than the shroud velocity. In effect, the sampling system simply ignores changes in stack gas velocity because the shroud provides a constant-velocity environment for the sampling nozzle.

The main advantage of this concept is its simplicity and low cost. All of the components of the SASS train, except the probe, are unchanged. The new probe, additional ducting, and exhaust blower would be relatively

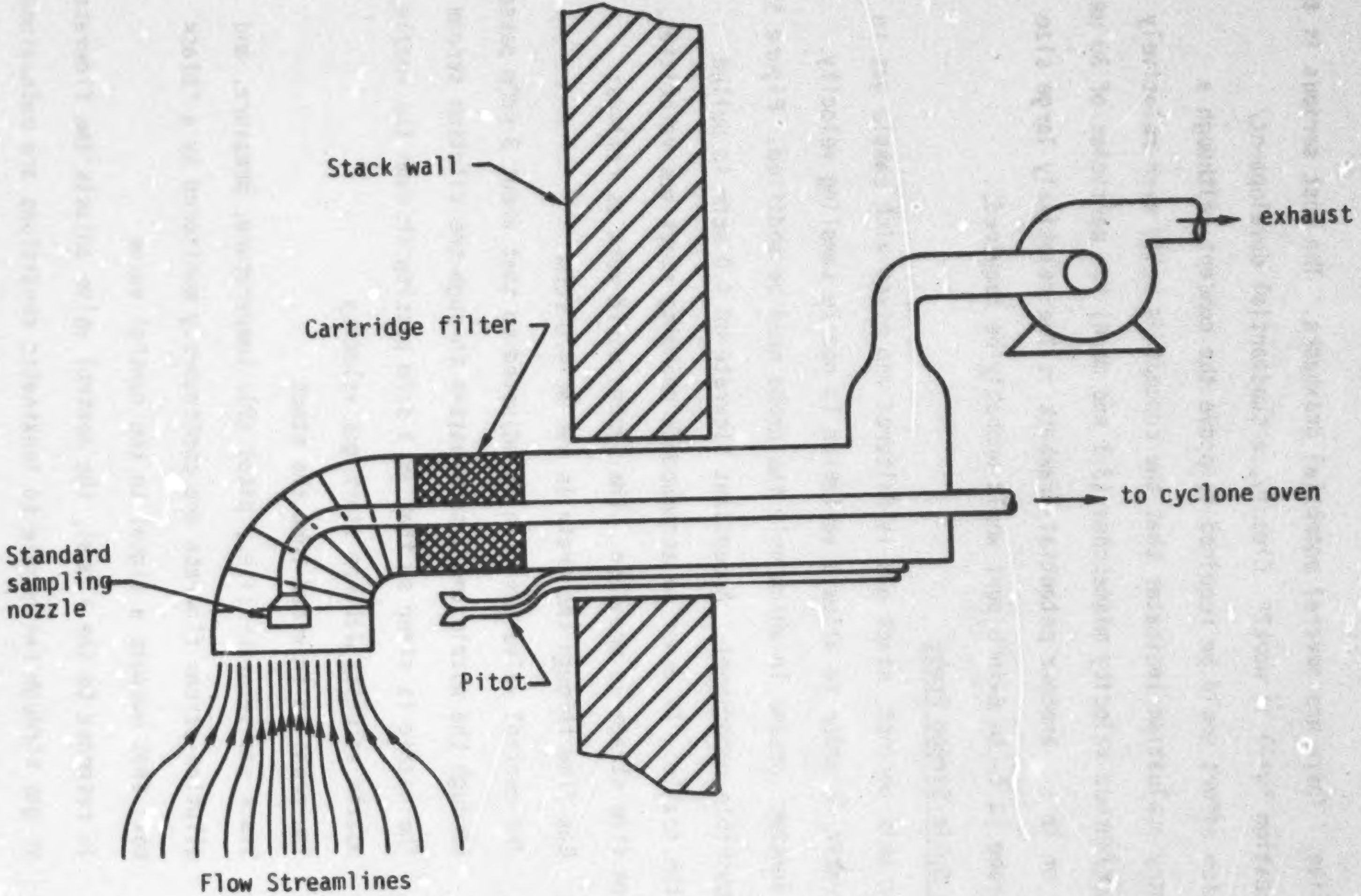
Stack wall
exhaust
Cartridge filter
to cyclone oven
Standard sampling nozzle
Pitot
Flow Streamlines

Figure 50. In-stack velocity control system.

inexpensive. There are several potential drawbacks. The most serious is the basic question "will it work?" Clearly, a substantial development/calibration effort would be required to prove the concept, although a preliminary evaluation indicates that the concept is valid over relatively wide stack/shroud velocity mismatches (3:1 and more) for particles of 30 μm diameter or less. Another potential drawback is the relatively large size of the probe (a 4- to 6-inch port would probably be required).

In-Stack Split Stream Probe

In this concept, stack gas is filtered and mixed with sample gas in varying ratio in order to allow a variation in nozzle sampling velocity. This is another concept in which only the probe need be modified. Figure 51 shows a possible embodiment. A constant flowrate of 4.0 scfm is pulled through the nozzle. In order to accommodate changing stack gas velocities, a dilution side stream is provided. The system would work as follows:

- Gas flow through the train is set at 4.0 scfm
- The control valve position is adjusted so that about 3 scfm passes through the nozzle and 1 scfm passes through the dilution stream
- The nozzle is sized so that at 3 scfm passing through the nozzle, nozzle velocity matches stack gas velocity
- The probe is inserted into the stack
- Stack gas velocity (i.e., pitot ΔP), temperature, pressure, and dilution-stream flowrate are continuously monitored by a "black box" that outputs a signal to the control valve
- In response to the signal, the control valve adjusts the flowrate of gas through the nozzle so isokinetic conditions are maintained. Since constant flowrate through the train is maintained by the

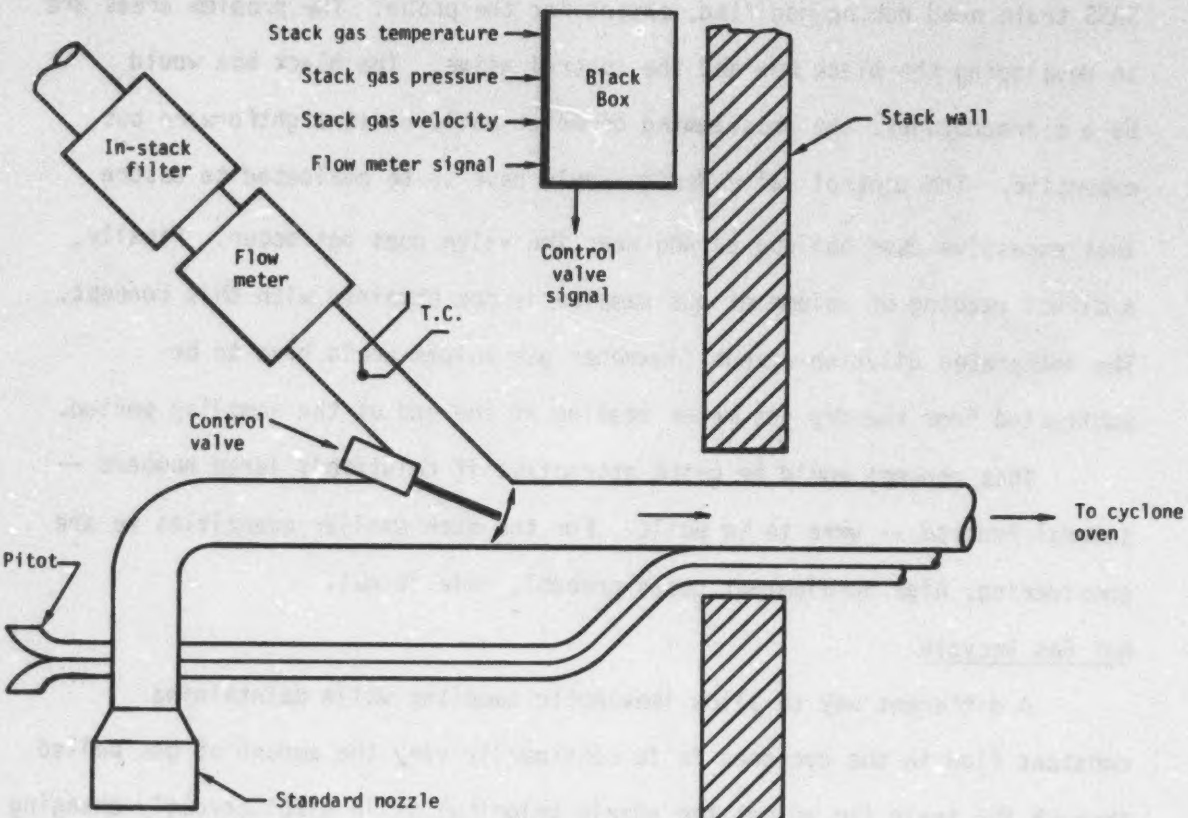
Stack gas temperature
Stack gas pressure
Stack gas velocity
Flow meter signal
Black Box
Control valve signal
Stack wall
In-stack filter
Flow meter
T.C.
Control valve
Pitot
To cyclone oven
Standard nozzle

Figure 51. In-stack split stream probe.

vacuum pumps, any increase (or decrease) in nozzle flowrate automatically causes an exactly corresponding decrease (or increase) in dilution-stream flow.

The primary advantage of this concept is relative simplicity -- the SASS train need not be modified, except for the probe. The problem areas are in developing the black box and the control valve. The black box would be a microcomputer, the programming of which would be straightforward but expensive. The control valve design would have to be evaluated to assure that excessive dust buildup on and near the valve does not occur. Finally, a direct reading of volume of gas sampled is not obtained with this concept. The integrated dilution-stream flowmeter gas volume would have to be subtracted from the dry gas meter reading at the end of the sampling period.

This concept would be quite attractive if relatively large numbers -- several hundred -- were to be built. For the much smaller quantities we are considering, high development costs probably rule it out.

Hot Gas Recycle

A different way to allow isokinetic sampling while maintaining constant flow in the cyclones is to continually vary the amount of gas pulled through the train (to adjust the nozzle velocity) while simultaneously changing the flowrate in a feedback loop around the cyclones. Figure 52 illustrates the simplest way to do this.

The SASS train is basically unchanged from its original configuration, except for the addition of the recycle loop. Isokinetic sampling is achieved by first choosing a nozzle size such that at 4.0 scfm through the nozzle, and for the maximum stack gas velocity expected during the test, stack gas and nozzle velocities are matched. The probe is then inserted into the stack,

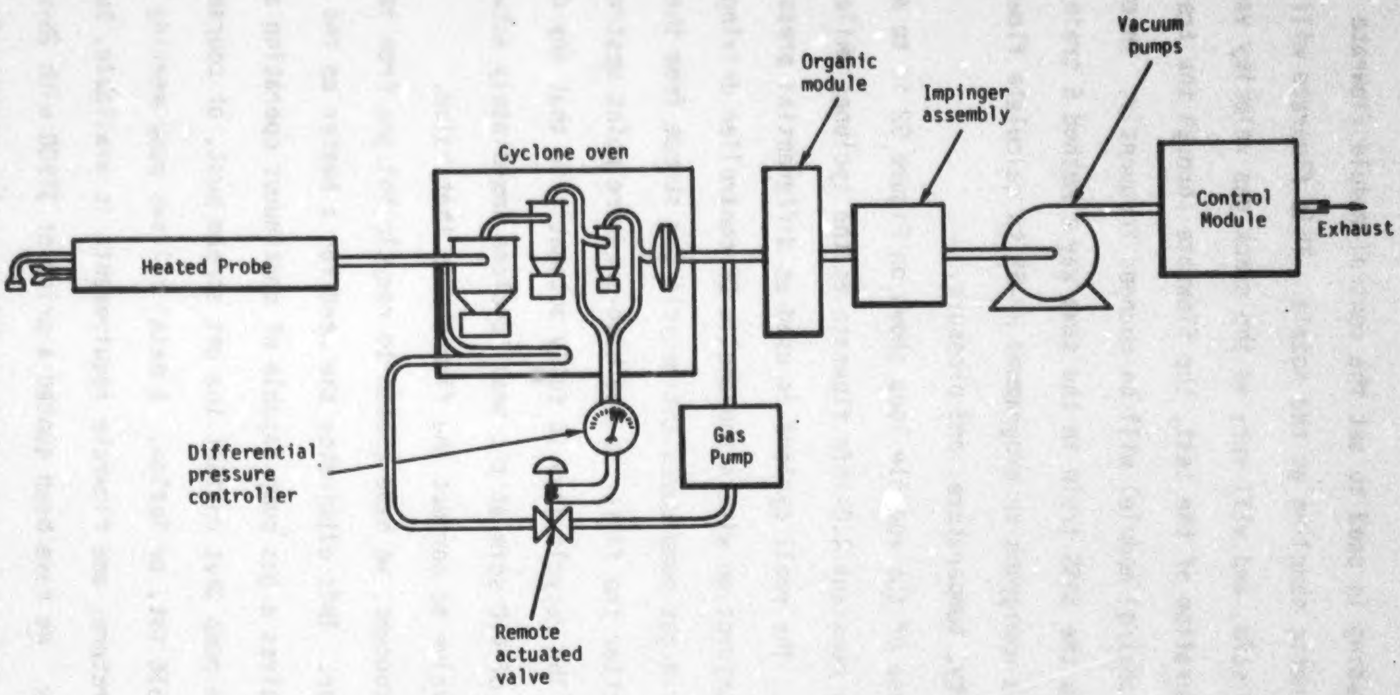
Cyclone oven
Organic module
Impinger assembly
Vacuum pumps
Control Module
Exhaust
Heated Probe
Gas Pump
Differential pressure controller
Remote actuated valve

Figure 52. Hot gas recycle.

and the pitot reading is used to set the control-module flowrate at a value that gives isokinetic sampling at the nozzle. This flowrate will in general be less than 4.0 scfm, and will vary as the stack gas velocity varies. Throughout the duration of the test, the flowrate through the train (as measured at the control module) will be changed frequently. In effect, we will be operating the SASS train in the same way a Method 5 train is operated, using a nomograph or programmed HP-65 to calculate flowrate from stack gas velocity, temperature, and pressure.

The purpose of the recycle loop shown on Figure 52 is to automatically maintain a constant 4.0-scfm flowrate at the cyclones while the train flowrate varies. The small cyclone is used as differential pressure flowmeter, in conjunction with a photohelic DP controller driving a remote actuated valve. A gas pump moves the recycle gas stream from the low-pressure point after the filter to the high-pressure point upstream of the first cyclone. The recycle loop is fully automatic in that any deviation from a flowrate of 4.0 scfm at the small cyclone immediately actuates the recycle stream valve to correct the flowrate to that value.

In this concept, we have chosen to recycle hot gas from immediately behind the filter. This eliminates the need for a heater on the recycle stream, but requires a gas pump capable of continuous operation at 400°F. The parts of the pump that contact the gas stream must, of course, be constructed of 316 sst, or Teflon. A metal bellows pump meeting the material, temperature, and flowrate requirements is available, but would be extremely costly. We have been quoted a price of $2900 with 26-week delivery in lots of 10. This high cost and long delivery time combine to make unattractive any concept utilizing a hot gas pump. Another drawback is the possibility of condensing organics or trace elements if any part of the recycle stream falls below 400°F. Also, a certain fraction of the vaporous pollutants in the sample gas will be recycled many times before being collected in the organic module and impinger train. The increased residence time in the sampling system increases the probability of catalytic or other reactive changes that could distort later pollutant analysis.

Cool Gas Recycle

One of the most serious problems with the hot gas recycle concept was the very expensive gas pump made necessary by the system material restrictions and the high temperature. In the cool gas recycle concept, this problem is overcome by recycling cool, cleaned gas from a downstream point in the train, as shown schematically in Figure 53. Its operation is similar to that described in the previous section for the hot gas recycle concept. The primary difference is in the recycle loop, where the gas pump now operates at ambient temperature, and a gas heater is required to raise the recycle loop temperature to 400°F before reinjection upstream of the cyclones.

Since the gas pump need not operate above room temperature, a wider choice of pumps is available. We have chosen a diaphragm pump as best meeting the system flowrate/pressure drop/materials requirements. In the particular pump chosen, all parts contacting the gas are 316 sst. except for a Teflon-coated neoprene diaphragm and Teflon check valves. The pump manufacturer has assured us that he has hundreds of such pumps in the field that have operated for several thousand hours with no cracking or other deterioration of the Teflon/neoprene diaphragm.

The reason we have chosen to use the small cyclone as a flow-monitoring DP device requires some explanation. First, the small cyclone is

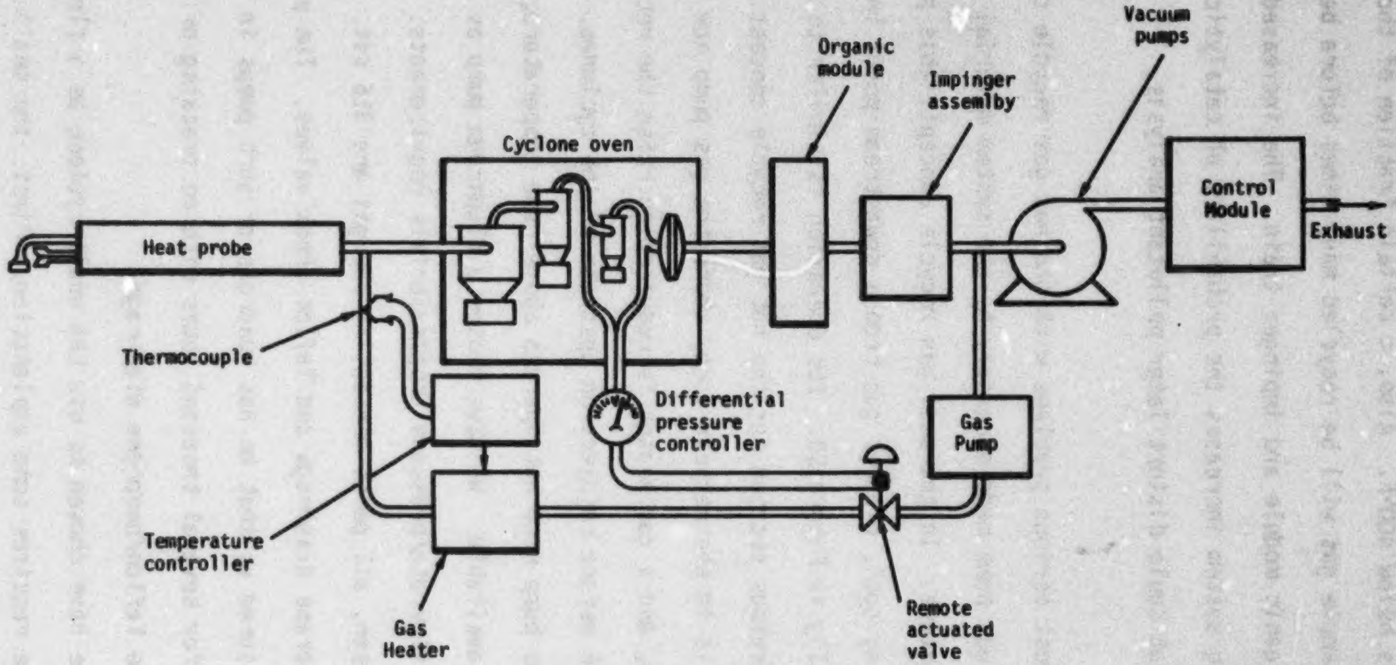
Heat probe
Thermocouple
Temperature controller
Gas Heater
Cyclone oven
Differential pressure controller
Remote actuated valve
Organic module
Impinger assemlby
Gas Pump
Vacuum pumps
Control Module
Exhaust

Figure 53. Cool gas recycle.

the highest ΔP component in the train with a nonvariable ΔP (this gives greatest sensitivity in the recycle flow control loop). Second, it is already in the train, so pressure taps may be added with a minimum of change and expense. Most importantly, there seems to be no good place to add another DP device such as a venturi or an orifice. Upstream of the filters dust buildup may be a problem. Downstream of the filter, the absolute pressure varies considerably during a run, so DP device characteristics will not be constant. For these reasons, the small cyclone seems now to be the best choice. Its use, of course, depends on the constancy of ΔP as dust builds up in the cup. This would have to be verified by calibration tests.

In both this concept and the previous one, less than 4 scfm of sample gas may be pulled through the train. For example, if the stack velocity is expected to vary by a factor of 50 percent during a sampling run (say between 67 and 100 ft/sec), then 4.0 scfm of stack gas will be sampled at maximum stack velocity, and 2.7 scfm will be sampled at the minimum velocity. The average flowrate during the sampling run will lie somewhere between, but is not predictable at the start of the test. The net effect is to lengthen the required sampling time to obtain a given total volume of sampled gas.

Comparison of Concepts

Table 16 shows an overview of the advantages and disadvantages of the various concepts considered. Taking all factors into account, concept 4, cool gas recycle, is recommended.

Figure 54 shows how the cool gas recycle concept might be implemented in one possible layout for an "Isokinetic Module." The isokinetic module will be packaged in a fiberglass case of dimensions 16 x 20 x 8 inches. It will weigh between 40 and 45 pounds, and will draw a maximum of 900 watts of

TABLE 16. EVALUATION OF CONCEPTS

Approach	Advantages	Disadvantages
1. In-Stack Velocity Control	• Low cost • Simple -- no modification to existing trains except to probe • Measures sample gas flowrate through trains • Pulls a full 4 scfm of sample gas	• Hard to get into stack • Does it really provide isokinetic sampling at the nozzle?
2. In-Stack Split Stream Probe	• All in-stack • Modification only to probe • Fully automatic isokinetic sampling	• Less than 4 scfm sample gas • Doesn't measure sample gas flowrate directly • Design of control may be difficult • High cost in small lots
3. Hot Gas Recycle	• Simple and cheap -- few components • Automatic flowrate control for cyclones • Totalizes sample gas volume	• "Dirty" gas is recycled • Air pump runs hot at high ΔP -- may not exist • Manual control for isokinetic sampling • Less than 4 scfm sample gas
4. Cool Gas Recycle	• Clean gas is recycled • Uses cool air pump • Automatic flowrate control for cyclones • Totalizes actual sample gas volume • Air pump must generate small ΔP only	• More components than design 3 -- somewhat more expensive • Manual control for isokinetic sampling • Less than 4 scfm sample gas

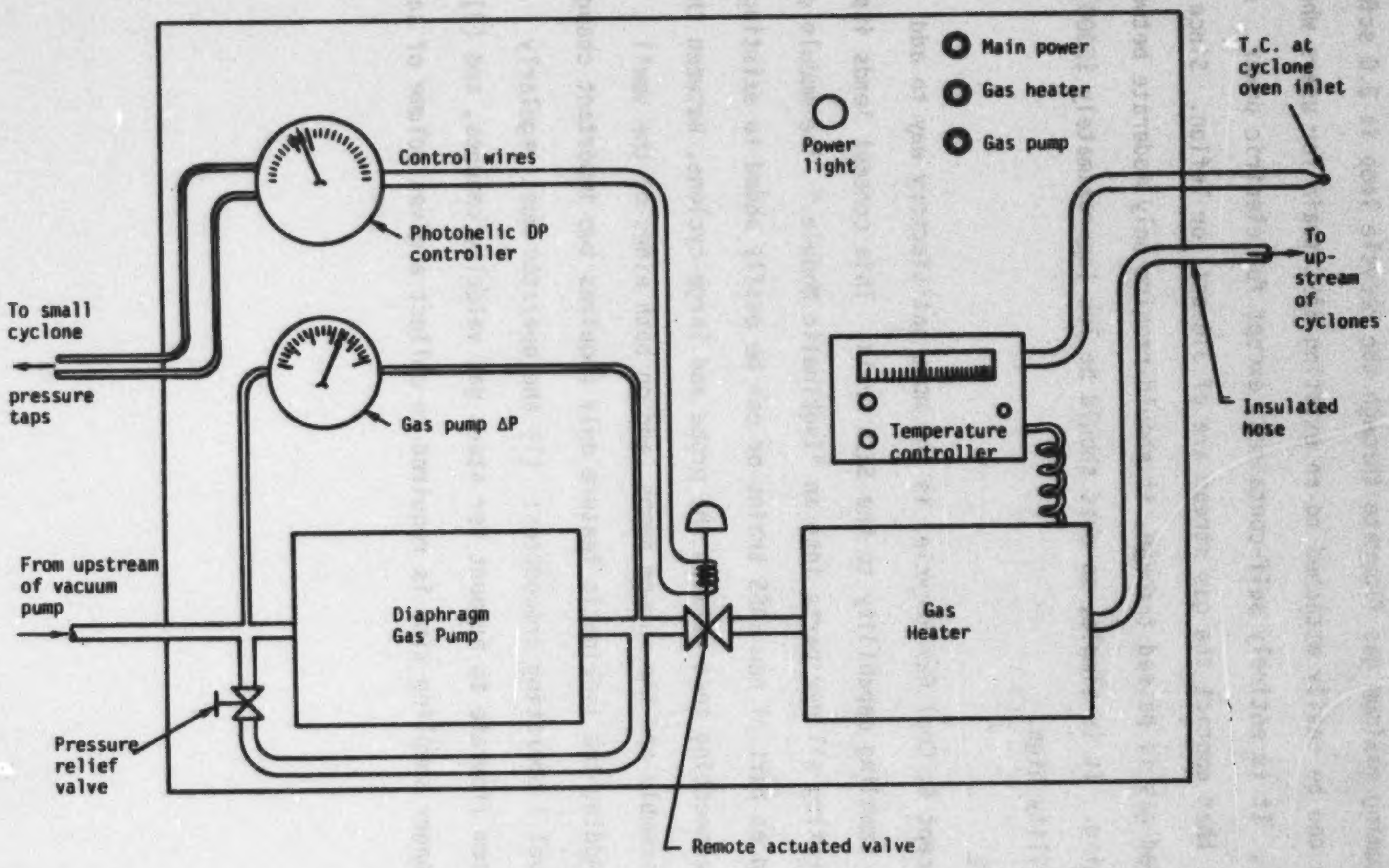
Main power
Gas heater
Gas pump
Power light
T.C. at cyclone oven inlet
To up-stream of cyclones
Insulated hose
Control wires
Photohelic DP controller
To small cyclone
pressure taps
Gas pump ΔP
Temperature controller
From upstream of vacuum pump
Diaphragm Gas Pump
Gas Heater
Pressure relief valve
Remote actuated valve

Figure 54. Schematic — isokinetic module.

power (assuming maximum gas flowrate through the recycle loop is 2.0 scfm). The module can be easily attached to an existing SASS train for users who require it. It is entirely self-contained, except for electric power. All components that contact the gas stream are of 316 sst. or Teflon. Since only cleaned gas is passed through, it should require only moderate between-test cleaning. It is simple, so cost should be low (approximately $5000) and reliability high.

Conclusions

Concept 4, Cool Gas Recycle, is the most satisfactory way to add isokinetic sampling capability to the SASS train. This concept lends itself to incorporating all new parts into an "Isokinetic Module." The module can be provided as part of new SASS trains or can be easily added to existing trains by connecting tees between the probe and large cyclone, between the impinger assembly and the vacuum pumps, and on both sides of the small cyclone. Adding the isokinetic feature only requires two important changes in SASS Level 1 operating procedures: (1) the operator must regularly adjust system flowrate to account for stack gas velocity changes, and (2) a slightly longer sampling time is required to collect a given volume of sample gas.

APPENDIX C

CONCEPTUAL DESIGN STUDY

As a part of a program to assess the emissions from a wide variety of stationary sources, the Environmental Protection Agency has established three source assessment levels. Each level of assessment serves a different purpose and may require different sampling and analytical instrumentation. Level 1 will provide semiquantitative screening of pollutant emission sources. The Level 1 Source Assessment Stack Sampler -- the end-product of this program -- will provide particulate, organic, and trace element samples for subsequent analysis. The particulate samples will be classified by particulate size; some of these sized fractions will be subject to toxicity, cytotoxicity, and trace element concentration analysis. The organic sample will be extracted from its adsorbent and classified into eight different classes of organic materials, on a semiquantitative basis. Similarly, the impinger solutions sample will be analyzed to determine the presence of metallic and inorganic pollutants.

The nature of Level 2 and Level 3 source assessment is less well defined, although the philosophy has been established. Level 2 assessment is indicated where Level 1 screening has shown the presence of a particular pollutant in significant amount or concentration. The source will be resampled -- either with the Source Assessment Stack Sampler or perhaps with a special sampling train -- and the collected sample carefully quantitatively analyzed for the significant pollutant. Level 3 assessment constitutes applying the current state of the art to detailed analysis of one or more pollutants. The most sophisticated techniques will be applied to elucidate every aspect of the nature of the pollutant.

The purpose of this Conceptual Design Study is to prepare a report describing several conceptual Level 1 Source Assessment Stack Sampler (SASS) trains. The goal is to determine if a SASS train costing about $15,000, and including all required features, can be built, and to predict the incremental cost required to add various control and convenience features. Both design and construction costs are important factors and are explicitly considered. Some of the ground rules that Acurex and the EPA have agreed as a basis for this design study are:

- The SASS train must perform the functions of sampling, determining particle size distributions into four size ranges, organic material collection, and trace element collection
- The cyclone assembly (designed on a previous program) and the organic collection module (designed as Task 1 of the present program) will not be modified (they may in fact be modified later, but for this report will be considered to have an established price)
- A wide range of possible SASS designs will be considered, from the simplest manual train to a fully instrumented train with semiautomatic flow control
- Manufacturing costs will be based on production runs of five units
- The cost of the SASS trains, at all functional levels considered, must be kept as low as possible. We have chosen four possible SASS designs for consideration. In the next section, each possible

design is considered in detail. The costs and operational attributes of each design are compared to Design B, which we recommend as the best compromise of price and performance. It should be noted that all of the price estimates made in this report are for comparison purposes only, and should not be interpreted as firm prices suitable for procurement purposes.

C.1 CONCEPTUAL DESIGNS

Design A offers the greatest number of features of the designs considered, and has the highest cost. It basically corresponds to the SASS train described in RFP No. DU-75-A303 and addressed in our Proposal No. 2146-75-B. Figure 55 shows a schematic diagram of the design. The key features are the semiautomatic flow controller (which maintains a constant flowrate through the cyclones despite changes in System P), the dual impinger train (to allow additional trace element collection solutions to be used), and the complete, centralized instrumentation readout capabilities. Two vacuum pumps are provided to allow use of very high pressure drop filter media. Table 17 shows a summary of the design features and costs.

The design costs for all four of the designs are based on the assumption that much of the component design will be completed on the present project. In general, design time required to build the incinerator trains and then to upgrade those trains to full SASS capability (by addition of probe, oven, and cyclones) will be charged to the present project; design time required to eliminate known problems will be charged to the current program. Redesign of problem areas (replacing stainless steel with aluminum), ovens (eliminating fan and remote temperature controller), and control modules (eliminating dry gas meters and orifice plates) for the

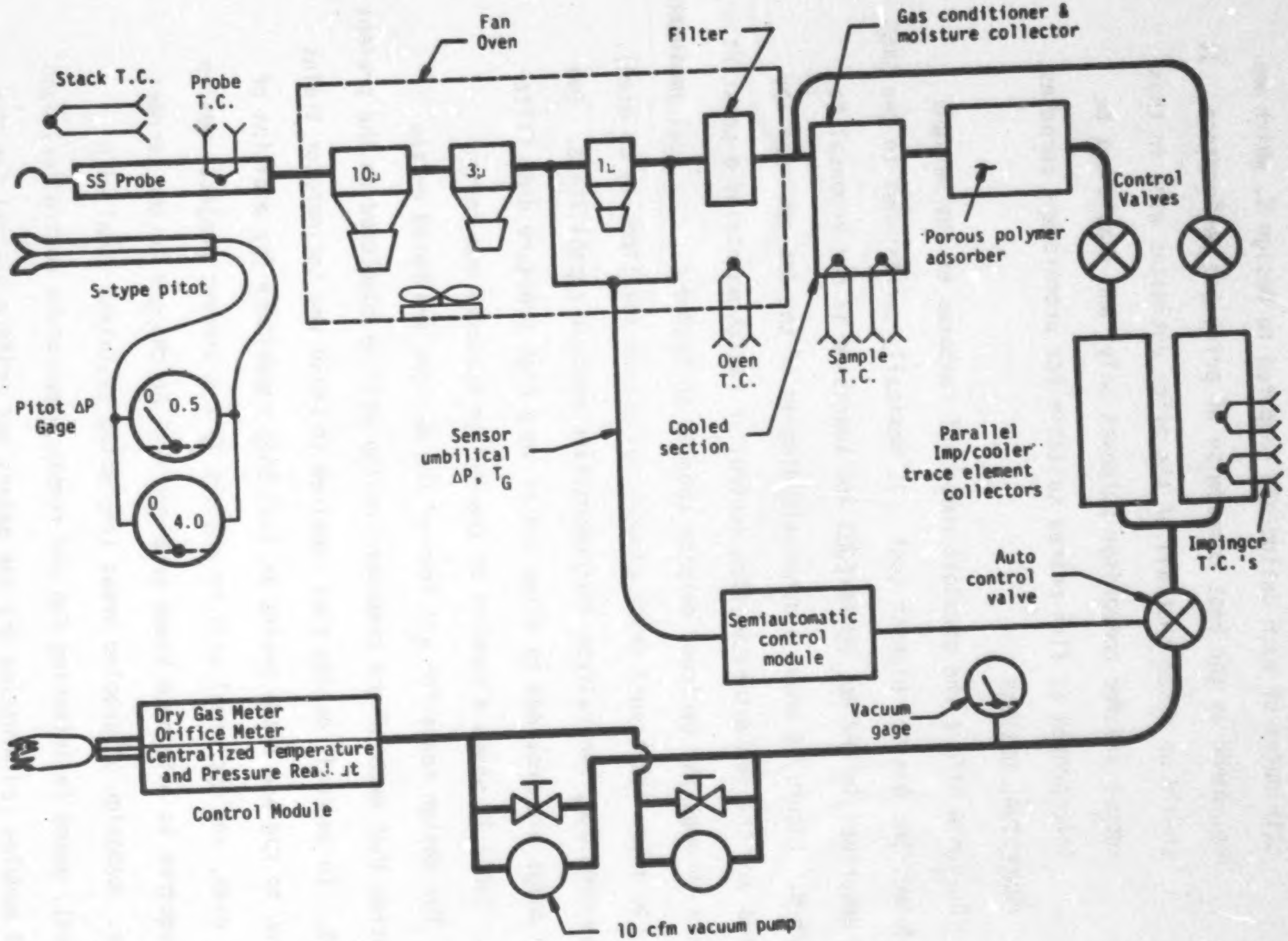
Fan
Oven
Filter
Gas conditioner &
moisture collector
Stack T.C.
Probe
T.C.
SS Probe
10μ
3μ
1μ
Control
Valves
Porous polymer
adsorber
S-type pitot
Oven
T.C.
Sample
T.C.
Pitot ΔP
Gage
0
0.5
0
4.0
Sensor
umbilical
ΔP, T_G
Cooled
section
Parallel
Imp/cooler
trace element
collectors
Impinger
T.C.'s
Auto
control
valve
Semiautomatic
control
module
Vacuum
gage
Dry Gas Meter
Orifice Meter
Centralized Temperature
and Pressure Readout
Control Module
10 cfm vacuum pump

Figure 55. Design A system schematic.

TABLE 17. DESIGN A SUMMARY

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Probe				
Stack thermocouple	—			
S-type pitot	—			
SS 316 nozzles (8)	—	Closer to isokinetic sampling.		+265
2-1/2" SS sheath	—			
Vycor liner	40	Noncontaminating at high temperature.		+200
Temp. controlled at control module	—			
Oven				
Large oven	—			
Circulation fan	—	Rapid warm-up.		
Temp. controlled at control module	—			
Cyclones				
3 standard cyclones	—			
ΔP instrumentation	—	Allows flow measurement by ΔP across small cyclone.	Redundant with dry gas meter.	
Filter Holder				
No teflon coat	—	No chance of contaminating analysis with teflon flakes.	Hard to clean.	
Special gasket	1	Allows use of thin filters.		+10
Gas Cooler & Tenax Module				
Standard design	—			
Impinger System				
Parallel impinger trains	—	Allows extended analysis of trace elements		+1230
Large glass bottles	—	Reduces carryover		+600
Extra instrumentation	60	Controls, monitors split flows to parallel impingers.		
Semiautomatic Controller	180	Completely untended operation.		+2500

*Compared to Design B

TABLE 17. Concluded

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Vacuum Pump				
Double vacuum pumps	—	Allows high ΔP filters.	Cost, weight.	+924
Extra connecting lines	16			+250
Umbilical Lines				
Standard umbilical	—			
Flow control umbilical	12	Necessary with semiautomatic flow controller.		+150
Control and Metering Module				
Pressure readouts	—			
Temp. readouts	—			
Temp. controller	—			
Orifice meter	—			
Dry gas meter	—			
Timer	—			
Fan control	—			
Power control	—			
Unirail	—	Allows positioning of probe for traversing.		+801

*Compared to Design B

purpose of reducing manufactured cost will be allocated to Design C or Design D as appropriate.

Design B, shown schematically in Figure 56, is the simplest SASS design that meets all of the functional requirements and is compatible with existing HVSS components. The semiautomatic flow controller of Design A has been eliminated, as have the duplicate impingers and vacuum pumps. The temperature and pressure readout and control functions have been chosen so a standard HVSS control module can be used. Table 18 summarizes the features and costs of Design B.

Design C is shown schematically in Figure 57. This design is a minimum interpretation of the basic SASS design. Numerous changes were made to reduce production cost. These changes include eliminating flow measurement devices from the control module (system flow is monitored by means of the cyclone pressure drop); providing aluminum, rather than stainless steel, sheathing for the probe; simplifying the umbilicals by provision of single power, thermocouple, and pitot connectors; and simplifying the oven by eliminating the convection fan and providing oven-mounted temperature control. These changes significantly reduce the cost of the Design C train; however, the ability to interchange components with existing HVSS trains is largely lost.

The features and costs of Design C are summarized in Table 19.

The final conceptual design considered, Design D, is an all-out attempt to achieve the lowest cost train possible. In this design (see Figure 58), the control module has been eliminated completely, and each component is locally controlled and monitored. The advantage of this concept is cost -- a sale price has been significantly reduced compared to Designs A, B, and C. The disadvantages are threefold: in general, the oration of the

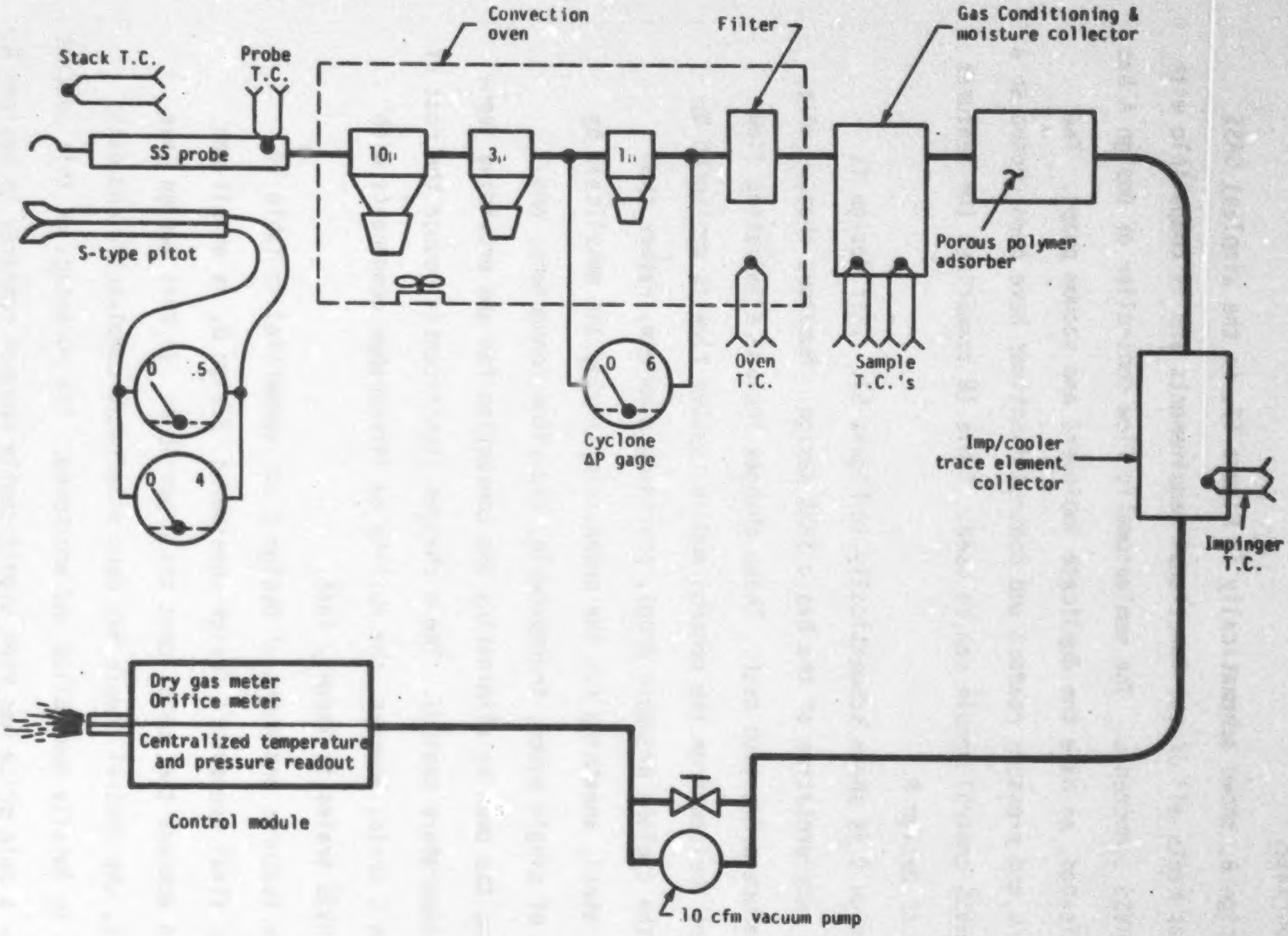
Convection oven
Filter
Gas Conditioning & moisture collector
Stack T.C.
Probe T.C.
SS probe
10μ
3μ
1μ
S-type pitot
Porous polymer adsorber
0
.5
4
6
Cyclone ΔP gage
Oven T.C.
Sample T.C.'s
Imp/cooler trace element collector
Impinger T.C.
Dry gas meter
Orifice meter
Centralized temperature and pressure readout
Control module
10 cfm vacuum pump

Figure 56. Design B system schematic.

TABLE 18. DESIGN B SUMMARY

Component	Design Hours	Advantage	Disadvantage
Probe			
Stack thermocouple	—		
S-type pitot	—		
SS 316 nozzles (3)	—		
2-1/2" SS sheath	—	Allows high sampling temps.	More expensive than aluminum.
SS 316 liner	—		
Temp. controlled at control module	—	Convenience, accuracy.	
Oven			
Large oven	—		Adds cost, weight.
Circulation fan	—	Rapid warmup.	Requires extra controls.
Temp. controlled at control module	—	Convenience.	
Cyclones			
3 standard cyclones	—		
ΔP instrumentation	—	Measures ΔP across small cyclone to monitor flow.	Redundent with dry gas meter.
Filter Holder			
Standard filter holder, no teflon coat	—	No chance for contamination.	Harder to clean filter holder.
Gas Cooler and Tenax Module			
Standard design.	—		
Impinger System			
Large glass bottles	—	Eliminate splash and carry-over, reduce contamination of solutions. Cost less than metal.	
Standard case	—		
Vacuum Pump			
Single standard pump	—		
Umbilical Lines			
Standard umbilical	—		
Control and Metering Module			
Pressure readouts	—	Standard control module.	
Temp. readouts	—		
Temp. controllers	—		
Orifice meter	—		
Dry gas meter	—		
Timer	—		
Fan control	—		
Power control	—		

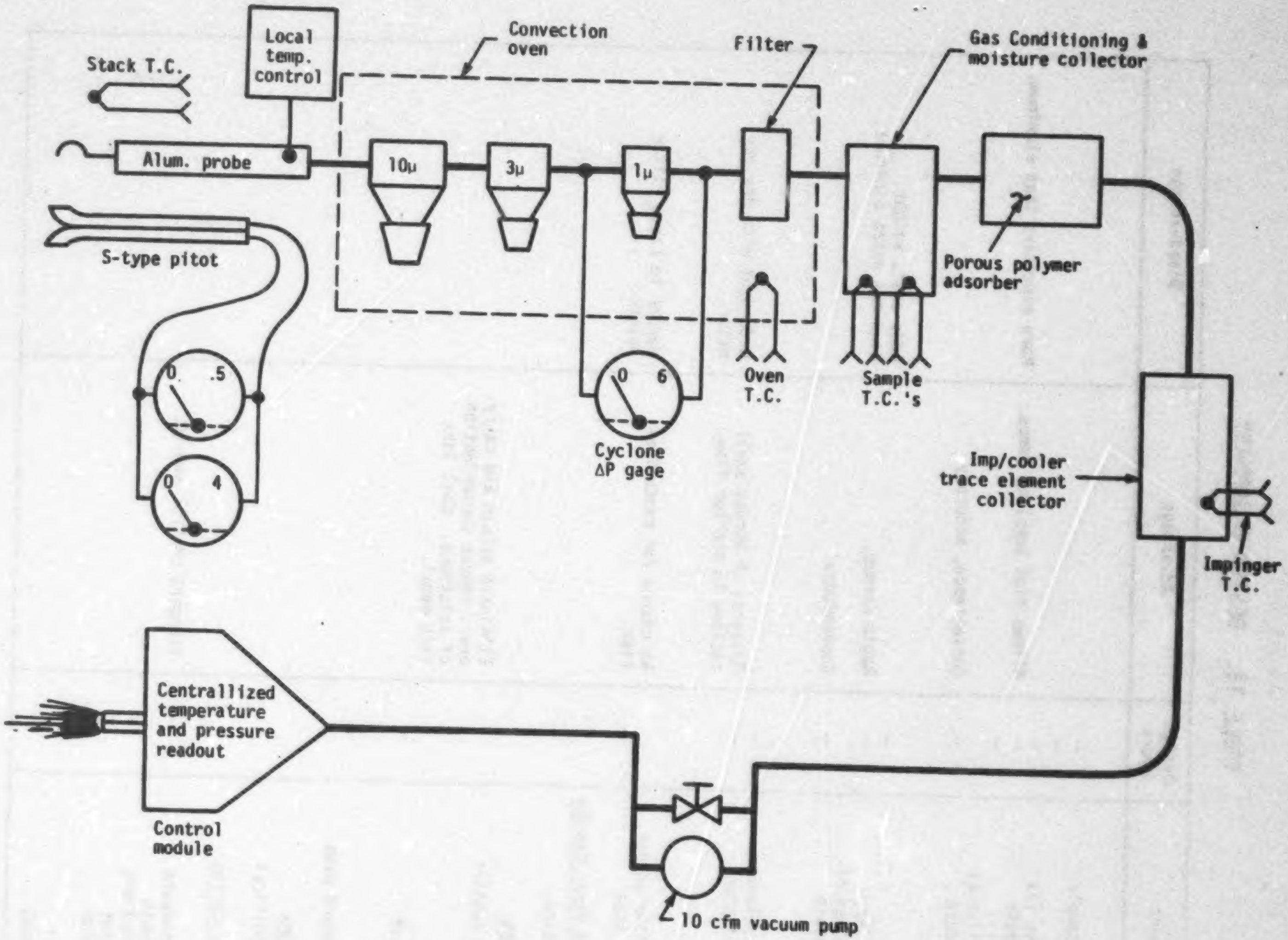
Stack T.C.
Local temp. control
Convection oven
Filter
Gas Conditioning & moisture collector
Alum. probe
10μ
3μ
1μ
Porous polymer adsorber
S-type pitot
0
.5
0
4
0
6
Oven T.C.
Sample T.C.'s
Cyclone ΔP gage
Imp/cooler trace element collector
Impinger T.C.
Centrallized temperature and pressure readout
Control module
10 cfm vacuum pump

Figure 57. Design C system schematic.

TABLE 19. DESIGN C SUMMARY

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Probe				
Static thermocouple	—			
S-type pitot	—			
SS 316 nozzles (3)	—			
2-1/2" aluminum sheath	4	Lower cost than SS.	Lower operating temperature. Not as corrosion resistant.	-44
SS 316 liner	—			
Local temp. control	28	Eliminates remote controller and connections.	Less convenient, less accurate.	-100
Oven				
Large oven	—			
No circulation fan	—	Lower cost, more room in oven.	Longer warm-up.	-20
Local temp. control	24	Eliminates remote controller and connections.	Less convenient, less accurate.	-100
Cyclones				
3 standard cyclones	—			
ΔP instrumentation	—			
Filter Holder[c]				
Standard filter, no Teflon coat	—			
Gas Cooler and Tenax Module				
Standard design	—			
Impinger System				
Large glass bottles	—			
Standard case	—			
Vacuum Pump				
Single standard pump	—			
Umbilical Lines				
Single power, thermocouple, and pitot connectors	60	Fewer lines needed on umbilical, lower cost, simpler connectors.	Interchangeability with standard HVSS system is lost.	-90

*Compared to Design B

TABLE 19. Concluded

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Control and Metering Module No dry gas meter No orifice plates & meter Timer Pressure readouts Temperature readouts Power control	180	Significant simplification of module.	Measurements less accurate, less central control, some sacrifice in interchangeability.	-1600

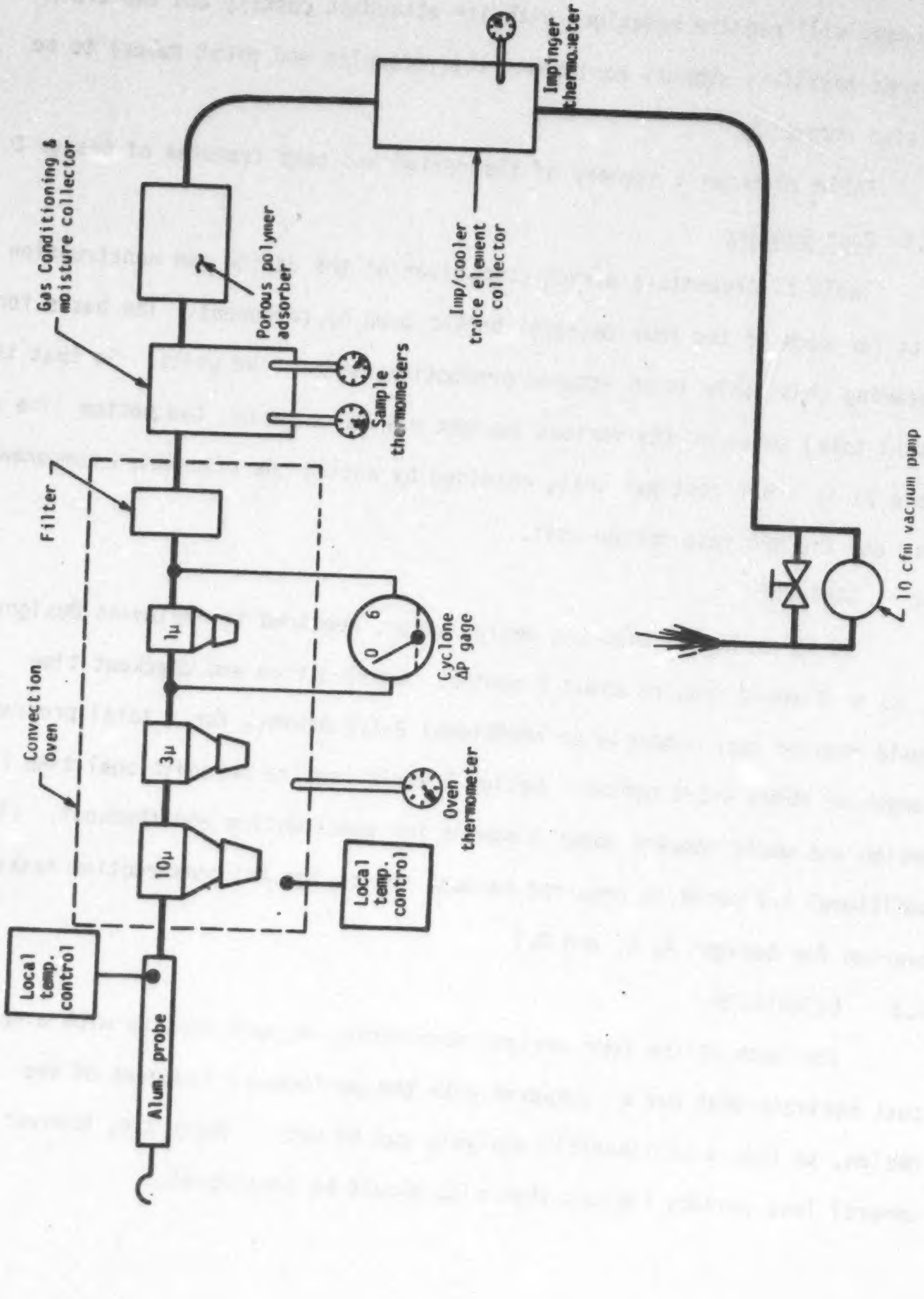
Local temp. control
Alum. probe
Convection oven
10μ
3μ
1μ
Local temp. control
Oven thermometer
0
6
Cyclone ΔP gage
Filter
Sample thermometers
Gas Conditioning & moisture collector
Porous polymer adsorber
Imp/cooler trace element collector
Impinger thermometer
10 cfm vacuum pump

Figure 58. Design D system schematic.

train is less convenient and less accurate than Designs B or C; nearly every component will require redesign (with its attendant costs); and the train requires auxiliary support equipment (thermocouples and pitot tubes) to be operated correctly.

Table 20 shows a summary of the design and cost features of Design D.

C.1.1 Cost Summary

Table 21 presents a direct comparison of the design and construction costs for each of the four designs, broken down by component. The basis for preparing this table is an assumed production run of five units. So that the actual total costs of the various designs may be compared, the bottom line of Table 21 is a net cost per unit, obtained by adding the discounted component cost and the pro rata design cost.

C.2 SCHEDULE

It is estimated that the design effort required to implement Designs A, C, or D would require about 2 months. Construction and checkout time would require approximately an additional 2-1/2 months, for a total program length of about 4-1/2 months. Design B would require no additional time for design and would require about 3 months for construction and checkout. (The additional 1/2 month is required because the design and construction tasks overlap for Designs A, C, and D.)

C.3 DISCUSSION

For each of the four designs considered, we have come up with a net cost estimate that can be compared with the performance features of the design, so that a cost/benefit analysis can be made. There are, however, several less obvious factors that also should be considered.

TABLE 20. DESIGN D SUMMARY

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Probe				
No stack thermocouple No pitot tube SS 316 nozzles (3) Heat-traced SS 316 liner Local temp. control	130	Considerably simpler, cheaper than standard probe.	Less accurate, less convenient.	-543
Oven				
Large oven	—			
No circulation fan	—			
Local temp. control	24			
Thermometers to measure oven, gas temps.	16	Low cost.	Less accurate, less convenient.	-120
Cyclones				
3 standard cyclones	—			
ΔP instrumentation	—			
Filter Holder				
Standard filter, no Teflon coat	—			
Gas Cooler and Tenax Module				
Standard design except thermometers except T.C.'s.	24	Low cost.	Less accurate, less convenient.	-180
Umbilical				
Power line only	16			-400
Impinger System				
Large glass bottles	—			
Standard case	—			
Vacuum Pump				
Single standard pump	—			
Sample hose	—			

*Compared to Design B

TABLE 20. Concluded

Component	Design Hours	Advantage	Disadvantage	Component Cost Change*
Control and Metering Body				
None	—	Reduced cost.	Reduced accuracy and convenience, local control of all components required.	-4020
Timer				
Separate timer box	24			+40

TABLE 21. SUMMARY OF COSTS FOR SASS DESIGNS

Component	Unit Cost, Lots of 5			
	Design A	Design B	Design C	Design D
Nozzles	$ 265	$ 159	$ 159	$ 159
5' Probe	1384	919	775	376
Oven	1500	1500	1250	1300
Cyclones	6070	6070	6070	6070
Filter Holder	395	385	385	385
Gas Cooler & Tenax Module	4000	4000	4000	4000
Impinger Trains	3060	1230	1230	1230
Umbilical	490	490	400	90
25' Sample Hose	95	95	95	95
Pump(s)	2098	924	924	924
Control Module	4020	4020	2420	—
Timer Unit	—	—	—	40
Unirail	801	—	—	—
Semiautomatic Controller	2500	—	—	—
Subtotal	26678	19792	17798	14669
less 12% System Discount	3201	2375	2136	1760
Total Component Cost	23477	17417	15662	12909
Design Hours Required	297	0	296	234
Design Cost @ $28/hr.	8316	0	8288	6552
Net Cost Per Unit*	25140	17417	17320	14219

*One fifth the design cost plus the discounted component cost.

In many cases, the organization that would purchase a SASS train would have a continuing need for both SASS and HVSS train capabilities. Often the potential SASS buyer will already have a HVSS train. It is clearly a desirable feature that as many components as possible in the HVSS be compatible with the SASS. This allows the user maximum flexibility in his sampling program, and -- if separate HVSS and SASS trains are procured --allows one train to be used as a backup and spare parts reserved for the other.

In many cases, the owner of HVSS train who desires to obtain a SASS will wish to buy only enough SASS components to upgrade his HVSS. In this case, the total cash outlay required to upgrade a HVSS is of interest. Table 22 shows the components that would have to be purchased to upgrade a HVSS to each of the SASS designs. Design D, because it is a radically different design than the HVSS, requires that an entirely new train be purchased -- the upgraded cost is equivalent to the discounted SASS cost (Table 21). Design C, which differs in several important ways from the HVSS, is also very costly to upgrade; the upgrade cost of $14,194 is only moderately lower than the SASS outright purchase price of $17,320.

For Design B, which was designed with HVSS compatibility specifically in mind, the upgrade cost of $11,570 is significantly lower than the SASS train cost of $17,417. Design A is also less costly to upgrade than to purchase a complete SASS train, although -- because of the many convenience features of Design A -- the upgrading cost is quite high. Table 23 shows the total cost to an organization that already has an HVSS to upgrade it to a SASS. It can be seen that the total cost for Design B is significantly lower than for any other train, even the stripped-down Design D.

TABLE 22. COSTS TO UPGRADE AN EXISTING HVSS TO FULL SASS CAPABILITY

Components to be Purchased	Cost			
	Design A	Design B	Design C	Design D
Vycor Probe Liner	424*			
Additional Nozzles	106			
5' Probe			954*	1104*
Oven	1500	1500	1384*	1524*
Cyclones	6070	6070	6070	6070
Gas Cooler and Tenax Module	4000	4000	4000	4000
Impinger System	2166*			140
Semiautomatic Controller	3508*			
Vacuum Pump	1264*			
Umbilical Lines			736*	180*
Control and Metering Module				
Umbilical Adaptors			1050*†	
Timer Unit				174*
Total Upgrade Cost	19038	11570	14194	13192

*Includes pro rata design cost.

†Adapts modified umbilical to standard control module. Two different adaptors required.

TABLE 23. TOTAL INVESTMENT REQUIRED TO UPGRADE A HVSS TO FULL SASS CAPABILITY

Design Type	HVSS Cost	Upgrade Cost	Total Cost
A	9040	19,038	28,078
B	9040	11,570	20,610
C	9040	14,194	23,234
D	9040	13,192	22,232

Another factor that should be considered when deciding which design is cost-effective is whether the SASS train will be used for some Level 2 source assessment. The system requirements for Level 2 sampling are not as well defined as for Level 1, but it seems reasonable to assume that measurement and control of sample flowrates will be more stringent. This is particularly significant when considering Designs C and D. In these designs, accurate flow measurement has been eliminated, making these trains of doubtful utility for Level 2 work. Designs A and B contain accurate flow monitoring components.

C.4 RECOMMENDATION

After considering all factors -- design cost, component cost, schedule, HVSS compatibility, versatility, and accuracy -- we believe that Design B is clearly superior to the others considered. We recommend that it be the basis for SASS train development.

APPENDIX D

CONVERSION FACTORS FOR NONMETRIC UNITS USED IN THIS REPORT

To Convert From	to	Multiply by
acfm (actual cubic feet/minute)	meter^3/sec	4.719×10^{-4}
Btu (British thermal unit)	joule	1.0544×10^{3}
cubic foot	meter^3	2.8317×10^{-2}
day (mean solar)	second	8640
Fahrenheit	Celsius	$C = (5/9)(F-32)$
foot	meter	0.3048
gallon	meter^3	3.785×10^{-3}
grain	kilogram	6.4799×10^{-5}
grain/cubic foot	kilogram/meter^3	2.2884×10^{-3}
horsepower	watt	745.70
hour (mean solar)	second	3600
inch	meter	2.54×10^{-2}
inch of mercury (60°F)	newton/meter^2	3376.85
inch of water (60°F)	newton/meter^2	248.84
lb_f (pound force)	newton	4.4482
(lb_m) pound mass	kilogram	0.4536
psi (lb_f/inch^2)	newton/meter^2	6894.76
scfm (standard cubic foot/ minute)	meter^3/second	4.719×10^{-4}

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